ECONOMIC GEOLOGY

VOL. XXX JANUARY–FEBRUARY, 1935 No. 1

GEYSER BASINS AND IGNEOUS EMANATIONS.[1]

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Introduction.—In the year 1847, when systematic observation on thermal springs was still in its infancy, Élie de Beaumont,[2] in an elaborate treatise on the distribution of the chemical elements in the crust of the earth, drew a clear outline of a hypothesis in which he ascribed the mineral substances of the metalliferous veins and thermal springs, as well as the water and heat of the latter, to volatilized constituents of eruptive rocks which had not yet cooled. Almost simultaneously Robert Bunsen [3] published the results of observations on the Icelandic hot springs, together with data from laboratory experiments, from which he concluded that the spring water was entirely meteoric, acquiring its heat by conduction through rock from a volcanic source; while the dissolved mineral matter, the sediments and deposits, were derived from the neighboring rock through the agency of the volcanic gases, sulphur dioxide, hydrogen sulphide and carbon dioxide. These two lines of thought concerning thermal springs, at times still more strongly divergent, have persisted up to this day.

Interrelated Features of Hot Spring Areas.—Hot springs are best studied by groups with related features; the springs them-

[1] Presented before the American Geophysical Union, Washington, D. C., April 26, 1934. Important parts of this article are taken from a forthcoming book: Hot Springs of the Yellowstone National Park, by E. T. Allen and Arthur L. Day. Microscopic examinations by H. E. Merwin.

[2] Des Émanations Volcaniques et Metallifères. Bull. Soc. Geol. de France (2), vol. 42, p. 1249, especially p. 1272, 1847.

[3] Ann. der Chem., vol. 62, p. 1, 1847.

selves, their discharge and associated topography, together with the characteristics of their thermal activity; the waters with their dissolved mineral matter, and the gases bubbling through them; the rocks in which the springs issue, as well as the deposits. All these are parts of one complicated system which we may call the *hot spring area.*

Types of Hot Areas.—Of the several types of hot area found in the Yellowstone Park, I propose to single out the geyser basin for special consideration here, as being nearest to the interests of most geologists.

There are two principal types of hydrothermal area; the sulphate tract, characterized by thin sandy or mealy deposits (generally quartz and other crystalline varieties of silica, but in places, opal), dotted with small, shallow, and commonly muddy springs with little aggregate outflow. The spring waters are dilute solutions of silica, sulphates of the common rock-forming metals and in many places free sulphuric acid, more or less choked with a sediment of opal and clay which is intermixed here and there with sulphur, pyrite, or hematite. The other important type of hot area is the geyser basin. Generally more extensive, it is distinguished by springs of the deep, clear variety, generally large and of high aggregate discharge. Fresh rhyolite outcrops occur about the borders of the basins and in places within their bounds, and rhyolite gravels may be seen in nearly all of them. No fracture approaching the dimensions of a fault finds expression in any of these areas, and in only one geyser basin has the trace of a local fissure been noticed. Ground formerly flooded with hot spring water is now covered with sheets and terraces of siliceous sinter or geyserite, that has commonly disintegrated into sands and gravels; the same deposit lines most of the springs and outlet streams, forms rings about many of the springs, and builds up mounds and cones around numerous geysers.

Spring waters in the geyser basins contain mineral matter averaging less than 1.5 g. per liter, consisting of silica and salts of sodium, with much smaller quantities of potassium and lithium and traces of calcium, the acid radicals being chiefly chloride and

bicarbonate, with lesser amounts of borate and fluoride, and arsenate only in traces. A distinguishing feature of these waters as compared with those of sulphate type is the great preponderance of sodium over potassium.

" Permanent " gases, which may be seen bubbling through the water of all thermal springs, consist in general of the same constituents; carbon dioxide, hydrogen sulphide, hydrogen, methane, nitrogen and argon. It is in the proportions of these that variations are found. Hydrogen sulphide, owing to the prevalence of conditions favoring oxidation, is rarely present in geyser basins, and hydrogen has been detected in only about one-fourth of the Yellowstone gas samples, irrespective of the type of ground. Carbon dioxide, which in sulphate areas usually exceeds the sum of all other permanent gases, escapes from these alkaline springs in much smaller quantities.

Development of Geyser Basins.—All these facts are important in framing a theory of thermal springs. Not only because of the difficulty in accumulating evidence, but also, I believe, because parts of the evidence have been lost sight of, have geologists reached such different conclusions. Arnold Hague, who saw in the veins of quartz, galena and copper minerals in the Miocene breccias of the Absaroka Mountains, deposits from igneous emanations, failed to perceive any similar relation in the salts of chlorine, sulphur and boron that occur in the Yellowstone hot springs just to the west of this range. He regarded all the elements in the thermal waters as leached from the adjacent rock or brought in by the waters from surface sources.

Lingdren's Theory[4] *of Hot Springs.*—Of those theories which lay stress on magmatic influences, Lindgren's is in some ways the simplest. He supposes that the spring waters ready-formed and heated are expelled from the magma by steam pressure. Data bearing on the question whether the steam exhaled by a magma in the high-temperature range may be transformed into a liquid phase at lower range, because of a critical temperature and the high pressure resulting from the resistance the steam must overcome in forcing its way to the surface, are of course rather

[4] Lindgren, W.: Mineral Deposits, p. 100. New York, 1928.

meager. Morey [5] is led by his experiments to the conclusion that critical conditions do not apply to the problem. That no such change in phase has occurred in the magma underlying the hot areas of the Yellowstone Park, is an inference that seems to follow from several lines of evidence.

1. If all hot springs originate in aqueous magmatic solutions, there appears to be no rational way to account for the superheated steam which, in certain hot areas outside the geyser basins, is escaping from natural vents.

2. If all hot spring waters are originally of a single type starting out from the magma ready-formed, the two distinct types, both dilute solutions, that actually come to the surface, remain unexplained.

3. Marked differences in the gases, characteristic of the two different types of hot springs, seem irreconcilable with the conception of an originally uniform spring water.

4. How can we neglect the fact that the alkaline areas of high discharge occur in well-defined drainage basins, where the most surface water would be expected, while sulphate springs are found on steep slopes where much of the rainfall would be lost as run-off, or in shallow depressions where only thin zones of ground water could accumulate?

This statement needs a little qualification. There are in every geyser basin a few sulphate springs, but they occur on the edges of the area, at a higher level than adjacent alkaline springs, where a more superficial circulation might be expected. In some sulphate areas, also, the presence of one or more deeper springs of different type points to differences in the depth of the circulating waters.

The majority of those who have given much attention to the investigation of thermal springs have regarded the water as derived from the rainfall, but Thoroddsen [6] appears to be the only observer except the writer who has seen a relation between topography and the type of spring. In Iceland, he says, the

[5] Jour. Wash. Acad. Sci., vol. 12, p. 219, 1922. Jour. Geol., vol. 32, p. 291, 1924. See also Morey and Fenner, Jour. Amer. Chem. Soc., vol. 39, p. 1173, 1917.

[6] Geschichte der Isländischen Vulkane, pp. 293–294. Copenhagen, 1925.

alkaline springs are generally distributed in the lowlands and valleys, appearing in this respect to follow laws similar to those which govern cold springs, whereas sulphur springs are common on steep slopes, ridges and peaks. The significance of these facts is believed to be that sulphur springs are chiefly "volcanic fumaroles," and carry volcanic vapors, whereas in the alkaline springs, surface water predominates. It seems strange that this relation, so obvious in the Yellowstone Park, should have escaped the notice of both Hague and Peale, since the surface origin of the thermal waters was recognized by each of them.

Hot Spring Discharge.—Impressed with the importance of ground-water supply as a factor in hot-spring development, we began several years ago the accumulation of numerical data. Obviously, only that portion of the rainfall which penetrates the ground is involved in the problem. Neglecting, for lack of a suitable method, the fraction of thermal water lost by evaporation, we undertook extensive measurements of the hot discharge in the Yellowstone Park, which resulted in a total of about 110 cu. ft. per second, after what is believed to be a substantially complete survey. This sum is regarded as a reliable first approximation.

Returning now to the problem of hot spring differentiation, we found that only 1.7 second feet of this amount was discharged by the sulphate areas, as compared with 77.7 second feet for the geyser basins and a few other allied alkaline areas with which we are now concerned. An accurate comparison of the extent of the two types of ground can not be given, but numerous observations involving many weeks of work show clearly that area for area, as well as in the aggregate, the alkaline localities are characterized by a higher—usually much higher—discharge.

Ground Water and Magmatic Steam in the Generation of Thermal Springs.—A hypothesis of the origin of thermal springs was published some time ago by the writer in collaboration with Arthur L. Day,[7] and here the evidence needs only a brief sum-

[7] Day, A. L. and Allen, E. T.: The Volcanic Activity and Hot Springs of Lassen Peak. Carnegie Inst. Wash. Publ. No. 360, p. 169, 1925. Allen, E. T. and Day, A. L.: Steam Wells and Other Thermal Activity at "The Geysers," California. Carnegie Inst. Wash. Publ. 378, p. 77, 1927.

mary. The association of thermal springs with natural steam jets in the higher and drier parts of the more arid hot-spring localities; the superheated character of some of these jets; the escape from thermal springs of volcanic gases similar to those which accompany steam in natural vents, in molten lavas, and in solidified igneous rocks; the enormous amounts of steam released by boring in hot spring regions, and its impressive gain in volume and temperature with increasing depth—all indicate that thermal springs are derived from circulating ground water heated by the condensation of magmatic steam. To judge from the mean annual temperature of the ground water and the maximum temperature of escaping steam in the Yellowstone Park, probably less than 15 per cent. of the water so heated is of magmatic origin.

Water Supply and the Depth to which it Penetrates.—A drill driven into the ground in hot spring and fumarole localities releases more and more steam, and with it more and more heat, the deeper it goes. Now, in a region characterized by a high potential steam flow, like most of the hot areas of the Yellowstone Park, it seems altogether probable that a small supply of ground water could not work its way down to any great depth without being wholly evaporated. What actually seems to occur is a descent to a level where its evaporation is balanced by the condensation of the magmatic steam that heats it; and the response of springs of small aggregate water supply to variations in the weather indicates that the depth is not great. Fenner found, when boring in sulphate ground at the Norris Basin, that the effects of this type of water disappeared within 30 feet.

In geyser basins, on the other hand, the greater magnitude of the water supply, as indicated by the discharge, would be expected to form a much larger body of ground water extending to greater depths; an expectation confirmed by the quantities of mineral matter continually carried away by the hot water, and the age of thermal activity implied by the thickness of the deposits and their slow accumulation. In a drill core taken from the Upper Geyser Basin, Fenner found the effects of thermal waters as far down as boring extended, namely, 400 feet.

Magmatic Emanations and Their Effects in Geyser Basins.—In attempting to draw conclusions regarding the magmatic emanations whose influence affects the hot areas under consideration, we have the testimony of hot waters, gases and altered rock. Reasons have just been given for concluding that steam is the predominant magmatic gas in hot spring localities. The sum of all other escaping gases; carbon dioxide, hydrogen sulphide, hydrogen, methane, nitrogen and argon, makes up a very small percentage of the whole. A test in the hottest steam vent of the Park showed only 0.4 of one per cent. The steam is doubtless not all magmatic; some of it is evaporated ground water. In the superheated steam wells of California the minimum amount of steam was 98 per cent.

The methane in the gases may not all be of magmatic origin, and the nitrogen is certainly not entirely so, but both these gases, as well as hydrogen and argon, are completely inert under the prevailing conditions. Carbon dioxide and hydrogen sulphide, as we shall presently see, have a part in chemical reactions.

Turning now to the dissolved material in the hot waters, we find six elements, none of which occurs in the neighboring rock in more than traces; carbon in bicarbonates, sulphur in sulphates, boron in borates, arsenic in arsenates, chlorine in chlorides, and fluorine in fluorides. Only two of these, carbon and sulphur, appear in the permanent gases, but it is a significant fact that all the others, as well, are found in hot fumaroles in the gaseous state; boron as boric oxide, chlorine and fluorine as the halogen acids, and arsenic in a condition unknown. In the hotter stages of volcanism, chlorine commonly occurs as vaporized sodium and potassium chlorides; both are found in sublimates from molten lavas and in the cavities of ejecta from active volcanoes.

Rock Alteration as Evidence of Igneous Emanations.—Until the boring tests in the Park were undertaken by the Geophysical Laboratory in the years 1929 and 1930, it had been concluded that all the silica and the metals in the Yellowstone thermal waters were leached from the adjacent rhyolite. In the sulphate areas it could hardly be doubted that the rock was in process of leaching

by sulphuric acid. Similarly, carbonic acid in the alkaline areas was believed to act selectively in leaching the rhyolite rock below ground, removing sodium in preference to potassium, and leaving in the residue a mineral or minerals higher in aluminum as well as in potassium, for aluminum is carried away by the spring waters only in traces. Rhyolite changing into clay in a few alkaline springs formed the chief support for this assumption.

Fenner's highly interesting studies [8] of the drill cores secured in the tests just referred to, showed that this hypothesis, or rather its generality, was untenable. They proved satisfactorily that an intensive rock alteration was in progress in the Upper Basin, involving, not a selective leaching by carbonic acid, but a replacement of sodium by potassium. At the same time these studies made it clear that little if any other kind of alteration was going on in the rock explored, except a transportation and deposition of silica. That the alteration is due to the action of potassium salts can hardly be questioned. The spring waters low in potassium, as they escape from the ground, must be much richer in that element at deeper levels, and its deposition in the rock, in place of sodium removed, satisfactorily explains the preponderance of the latter in springs of this type.

Origin of the Potassium Salts.—That the potassium, along with sodium, is volatilized by the magma as chloride, with other gases already considered, is the most reasonable view that can be expressed on the basis of present knowledge. These chlorides are supposed to be dissolved at the lower limit of the body of ground water, whence they are carried upward by hydrostatic pressure and by circulating currents, wherever channels are wide enough to permit of it. As the solution moves through the cracks and pores of the rock, alteration by replacement proceeds in the manner that Fenner has described.

The obvious objection to this derivation of potassium and sodium is the low vapor pressure of the halides at red heat. If they are transported in this way, the tenuous vapors must be swept upward by excess of steam. It may also be true that cracks

[8] Trans. Amer. Geophys. Union, 15th ann. meeting, 1934, p. 241.

and fissures in the rocks were filled by sublimates of the alkali halides in an era of higher temperatures, and that these deposits are now being drawn upon by the circulating water, but whether any deposit of such high solubility could supply the waters indefinitely may be doubted.

That this difficulty may be obviated by the assumption that both halogens are volatilized from the magma as the corresponding acids, and that the alkalies are removed from a portion of the overlying rock by the attack of these acids, is a suggestion that may come to mind. The assumption is satisfactory as far as present-day processes are concerned; the difficulty is to account for earlier stages of rock alteration on this basis. Exploration has not yet extended below a level of 400 feet. Somewhere at a lower level the halogen acids may be transforming another zone of rhyolite into silica, with the simultaneous formation of soluble chlorides. Farther up, the acid solutions may be neutralized and may become alkaline, bringing only the alkali chlorides to still higher levels, where the alteration of rhyolite by replacement is probably still in progress. But at the time when the rhyolite flows had only cooled enough to permit the formation of a thin zone of hot ground water, it would seem that the volatile acids rising and dissolving in this water must have leached the rock to silica, or what is less probable, that it may have removed sodium in preference to potassium, leaving a mineral or minerals in which the molar ratio of alkalies plus lime, to alumina, must have been smaller than it was in the original rock. The process of alteration, whatever it was, should have continued to this day, as the ground water slowly penetrated to lower levels. But no such processes have left their record in the altered rock.

Whether alteration is effected by alkali halides or indirectly by halogen acids, the assumption that hot springs originate in an aqueous magmatic solution, consisting chiefly of silica and sodium chloride, leaves out of account one important factor in the problem, namely; the *rock* through which the hot spring waters come to the surface. The enrichment of the rock in potassium shows

that this element was an important constituent of the ascending waters.

Bicarbonates[9] *in Alkaline Spring Waters.*—Although the altered rock studied by Fenner shows little indication of reaction with carbon dioxide (except the solution of silica), it is quite evident from the composition of the hot waters that such a reaction is somewhere in progress, for the average alkaline spring water in the Park contains 7 equivalents of the bicarbonate radical for every 10 equivalents of the chloride radical. Supplementary testimony to the same effect may be seen in the relation of gases to spring waters in each type of hot area. In sulphate areas considerable gas escapes from the hot waters, and since the permanent gases are chiefly carbon dioxide, much free carbon dioxide in sulphate springs is associated with little or no combined carbon dioxide dissolved in the water. In alkaline springs of the geyser basins, on the other hand, we find remarkably little free carbon dioxide associated with much of that gas combined as bicarbonate in the water.

Reduced Volume of Gas in Alkaline Springs due to Absorption of Carbon Dioxide.—That the extremely small amounts of free gases rising in the springs of the geyser basins is due to an absorption of carbon dioxide below ground, and not to source variations in different places, is revealed by a study of the gases themselves.

An approach to the composition of the original permanent gas in sulphate areas was made by averaging sixteen selected analyses lowest in nitrogen and probably least contaminated by air. From the average was subtracted a small amount of air equivalent to oxygen present. The problem was to show whether or not the gases collected from geyser basins could be derived from the average uncontaminated gas of sulphate areas by the mere absorption of carbon dioxide. Six gases from geyser basins, chosen because of their high nitrogen and methane, all contained considerable air. When this had been subtracted from the analyses there remained residues of carbon dioxide, nitrogen, argon and

[9] By thermal dissociation of bicarbonate in springs of high temperature, where rising carbon dioxide is very slight, some carbonate is formed.

methane, all of which could be approximately duplicated by the removal of a definite but variable amount of carbon dioxide from our so-called "original magmatic gas." Allowance had to be made for lack of hydrogen and hydrogen sulphide in the gases considered, but the proportions of nitrogen and methane remained substantially what they were in the "original gas," when the carbon dioxide was reduced to the values shown in the gases collected from geyser basins. To obtain these values an average of well over 90 per cent. of the carbon dioxide had to be removed.

The evidence strongly indicates that the magmatic emanations in the Yellowstone Park, so far as the permanent gases are concerned, are at least approximately uniform; and that the small volume of escaping gases in geyser basins, and the relatively high percentages of methane and of nitrogen plus argon in these localities is due to the absorption of carbon dioxide below ground.

A Second Type of Rock Alteration.—Another inference from the same facts is that somewhere below the surface of alkaline areas a second type of rock alteration is going on, in addition to that discovered by Fenner. He points out that the molar ratio of alkali plus lime to alumina, which approaches unity in the fresh rhyolites, is retained, at least very nearly, in the altered material. A chemical attack by carbonic acid would undoubtedly result in the formation of alkali bicarbonate, leaving some mineral or minerals higher in alumina, since practically none of the latter is carried away by the water. As previously remarked, such a reaction yielding clay has been found in a few Yellowstone alkaline springs, and a slight fall in Fenner's molar ratio points in the same direction, but it is quite evident that most of the rock altered by carbonic acid must lie below the limit of present exploration.

At the Norris Basin, where Fenner found a similar type of rock alteration beginning some 30 feet below the surface, temperatures and pressures in the closed bore hole were higher than they were in the Upper Geyser Basin at the same depth, and there is reason to think that the zone of ground water is shallower. In the alkaline waters of the Norris Basin, the bicarbonates are

much lower in concentration (averaging only one-eleventh that in the Upper Basin) than they are in any of the other geyser basins, and the free gas is greater in amount. Perhaps this means that less carbon dioxide is absorbed in reaction with the rock because its path through ground water is shorter. Whatever the reason, observations show beyond question that the action of carbon dioxide on the rhyolite varies greatly in different places.

Solution and Transportation of Silica.—Hot waters containing soluble bicarbonate would naturally dissolve silica from the deeper zones of rock where temperatures are high, and although the further behavior of the solution could not be certainly predicted, the deposition of quartz with falling temperature at higher levels is not improbable, and is in perfect accord with the actual increase of silica, and the appearance of secondary quartz in the altered rock studied by Fenner. Further deposition of silica as geyserite at the surface, and in the uppermost zone of the rock, is controlled by factors only partially understood. Evaporation, freezing, and at least one other factor, are probably operative, while considerable silica is carried away in solution by the drainage.

Absence of Acid Leaching in Alkaline Areas.—Hydrogen sulphide in alkaline springs seems to pass by oxidation directly into alkali sulphate, whereas in sulphate areas it takes the form of free sulphuric acid. This accounts for the lack of acid leaching in geyser basins.

SUMMARY.

In this interpretation of the facts I have endeavored to show:

1. That the character of the magmatic emanations in the Yellowstone geyser basins, and their function in hot-spring development, can be deduced from available evidence.

2. That these emanations are all in the gaseous state when they leave the magma.

3. That the water of these geyser basins is largely (perhaps 85–90 per cent.) of surface origin, and because the supply is

large, it descends to depths which a small supply could not attain without being wholly evaporated. At such depths the water dissolves and brings upward substances of low volatility, either magmatic sublimates or compounds formed at deep levels.

4. That the rock of these drainage basins is an important factor in the development of the alkaline springs, yielding all the silica in both waters and deposits, and at least an important part of the sodium in the former. This follows from the work of Fenner.

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THE TIN DEPOSITS OF LLALLAGUA, BOLIVIA.[1]

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PART I.

CONTENTS.

Introduction 14
Geology of the district 16
Structural geology of the veins 20
Hydrothermal metamorphism 32
General description of the ore deposit 36
The vein minerals and their paragenesis 38

To be continued in next number.

INTRODUCTION.

THE present article is based upon field work covering a period of three years (1927–1930), followed by a microscopic examination of the ores and rocks at Harvard University. Its purpose is to give a detailed account of the ore deposit, with special reference to mineral paragenesis and origin, and to correct certain inaccurate statements that have appeared in the literature. The accompanying plans, which date from 1929, have been considerably generalized and idealized, but the field facts which they illustrate have not been distorted.

Location.—The Bolivian tin and silver mineralization extends along the ranges east of the high plateau, from Lake Titicaca to the Argentine border. Northeast of Oruro, the principal metal is tin, with local concentrations of bismuth and zinc; and the deposits, in the main, are genetically related to granitic intrusives which cut the Palaeozoic sediments. South of Oruro, the mineralization is largely associated with quartz porphyry intrusives; and, if more accessible, the area would be known as much for its

[1] Emmons Memorial Fellowship Publication. Abstract of a Ph.D. Dissertation, Harvard University, 1933.

This manuscript was received prior to the publication of "The Llallagua-Uncia Tin Deposit," by Victor Samoyloff, published in No. 5, August, 1934.—EDITOR.

diversity of metallization, with tin, silver, gold, lead, zinc, bismuth, and antimony, as for the unique association of tin and silver.

The Llallagua district is located approximately in the center of the mineralized belt, and about 75 miles southeast of Oruro. It is connected by rail with Machacamarca, a point south of Oruro on the Antofagasta and Bolivia Railway. Salvadora Mountain forms the center of the district, with the village of Uncia at the edge of a broad valley to the southeast and Llallagua at the foot of the mountain to the north.

Mining Operations.—Previous to 1924 two companies, the Cia. Minera de Llallagua, and the Cia. Estañifera de Salvadora, the latter owned by Mr. Simon I. Patiño, were working essentially a single system of veins; but in 1924 these were combined under the Patiño Mines and Enterprises Consolidated. In recent years, this company, utilizing modern methods, has accounted for nearly one half of the tin production of Bolivia and for approximately one tenth of that of the world. A review of the operations of the company has been given by Beard,[2] but the following statistics, taken from the Annual Reports, may be of interest:

Year	1929	1930	1931	1932
Development, Meters	25,346	21,521	22,767	16,448
Ore Mined, Metric Tons	986,620	787,678	575,656	335,563
Tin Produced, Long Tons	20,800	17,015	14,355	8,061
Grade of Ore, per cent	3.05	3.06	3.35	3.09

Physiography.—Northeast of Oruro, the Eastern Cordillera, known as the Cordillera Real, is a rugged snow-capped range of Alpine grandeur with many peaks rising above 19,000 feet, but to the south it is made up of several distinct ranges and isolated peaks, with summits seldom more than 16,000 feet high.

The Llallagua district is located in the southern region a few miles east of the divide, where the ridges present a general conformity of line suggesting a dissected plateau. The older surface

[2] Beard, R. R.: Property and Operation of Patiño Mines and Enterprises at Llallagua, Bolivia. Eng. & Min. Jour., Aug.–Sept., 1930.

of erosion lies below the principal peaks of the region but it is preserved beneath nearly horizontal volcanics which cap many of the ridges. Elevations in the district vary from 12,000 to 15,500 feet, but the mountain slopes are moderate and the summits easily accessible. For the most part, the valleys are broad, but the present streams have cut narrow channels in the extensive gravel deposits, and the Uncia River, where it crosses a prominent sandstone ridge, has formed a canyon three hundred feet deep.

GEOLOGY OF THE DISTRICT.

The geological setting of the tin deposit of Llallagua is relatively simple. The ore occurs in a great network of veins within and contiguous to a small quartz-porphyry stock, which forms the core of Salvadora Mountain.

Most of the district is underlain by sedimentary rocks folded into a broad anticline striking northwesterly. The easterly limb of the fold is vertical or sharply overturned, whereas the westerly limb dips about 60°. A dark sericitic quartzite at the base outcrops as a broad belt up to 1,500 meters in width, thus marking the axis of the fold, and it is followed by sandstones, shales, and "red beds." The Salvadora quartz porphyry forms an oval area slightly southwest of the axis and at most mine levels is completely surrounded by the sericitic quartzite.

The Sedimentary Rocks.—The basal quartzite is light gray to nearly black in color, with scattered quartz grains in a dark argillaceous matrix. It is unusually massive in appearance, and in places it shows a typical spheroidal weathering; but its sedimentary origin is clearly revealed by the microscope. Angular to poorly rounded quartz grains average about 0.7 mm. in size, and they are completely separated by an abundant matrix, which, in unaltered specimens, is composed of sericite and quartz. In specimens from the mineralized zone, the matrix includes tourmaline and coarse sericite, and the quartz grains are considerably replaced. Only a few fragments of sandstone were observed, and none of feldspar. Accessories include rounded zircon, subhedral pyrite, and rutile.

Overlying the quartzite with apparent structural conformity is a brownish sandstone some 200 feet in thickness. It is composed almost entirely of quartz, and although somewhat less metamorphosed than the older formation, it is more resistant to weathering and caps many of the ridges. It grades upward into a series of sandstones and shales several thousand feet thick. Brown to buff sandy beds prevail in the lower part of the section, and light to dark gray shales in the upper part. A thin sandstone near the top, according to Koeberlin,[3] carries fossils of Devonian age.

The uppermost formation includes several hundred feet of red and dark brown conglomerates, with thin and irregular lenses of red sandstone. Lithologically the series resembles the mineralized "red beds" of Vila Apacheta,[4] 15 miles east of Llallagua, and Steinmann's Puca Formation,[5] which outcrops near Potosi and carries a Cretaceous fauna. At Llallagua the "red beds" appear in nearly horizontal position, and they mark the axis of a syncline which is parallel to the principal anticline.

The Salvadora Stock.—The tin ores of Llallagua are unquestionably related in origin to the Salvadora quartz porphyry, and perhaps 80 per cent. of the ore has come from veins within its area. Excluding a few dikes and sills which finger out into the sedimentaries, the porphyry measures 1,600 by 1,000 meters at the surface, but in depth its area is less and its contact more irregular.

The Salvadora intrusive is a cross-cutting body with the form of an inverted cone whose walls dip inward at steep angles. The abundance of breccia and the obscurity of chilled contacts indicate that explosive action was involved in its development; and these facts together with its form suggest a volcanic neck or crater.

The porphyry has produced only feeble contact metamorphism; at best, a silicification which is far less pronounced than the hydro-

[3] Koeberlin, F. R.: Private Report, Cia. Minera de Llallagua, 1919.

[4] Ahlfeld, Friedrich: Die Zinnerzlagerstätten Vila Apacheta. Zeit. f. prakt. Geol., vol. 39, pp. 33–37, 1931.

[5] Steinmann, G.: Geology von Peru, pp. 176–180. Heidelberg, 1929.

thermal alteration along the larger veins, even along those several hundred feet from the contact. The general weakness of contact action can be attributed to the small size of the intrusive, to the inert character of the sediments, and, even more, to the explosive origin of the stock.

The stock shows no evidence of having been folded, and it is therefore later in age than the Llallagua anticline, which involves the Cretaceous (?) red beds. In size, composition and association with ore it is similar to many intrusives of central and southern Bolivia, and in form also it is comparable with the Potosi vent,[6] which cuts plant-bearing beds of late Miocene or Pliocene age.[7] It may be inferred that the Llallagua intrusive is but one of several which outline a late Tertiary magmatic province extending southward from Oruro.

Although referred to as a unit, the Salvadora stock includes several rock types, which differ principally in the proportion of fragmental material that they contain. The principal rock type is a highly altered quartz porphyry, in which all original constituents except quartz have been replaced by sericite, tourmaline, and secondary quartz. The residual quartz phenocrysts average 2.5 mm. across, and many are deeply embayed. Where alteration is intense, they are fringed with secondary quartz and invaded by tourmaline and sericite. The feldspars are now represented by a tourmaline-sericite-quartz aggregate. No vestige of polysynthetic twinning exists, but in one thin section of a marginal dike, a zonal structure is reproduced, and in another several albitized plagioclase phenocrysts and a single albite crystal remain. The ferro-magnesian phenocrysts have been replaced by coarse tourmaline, sericite, quartz, and rutile, in aggregates of elongated outline indicating original biotite. The holocrystalline groundmass is commonly reduced to a fine network of the same secondary minerals, but in some highly altered specimens it consists almost entirely of tourmaline or quartz.

[6] Lindgren, Waldemar, and Creveling, J. G.: The Ores of Potosi, Bolivia. ECON. GEOL., vol. 23, pp. 233–262, 1928.

[7] Miller, B. L., and Singewald, J. T., Jr.: Mineral Deposits of South America, pp. 122–123. New York, 1919. Kozlowski, Roman: Bull. Soc. Geol. France, Ser. 4, vol. 23, pp. 57–62, 1923. Steinmann, G.: Geol. Rundschau, vol. 13, pp. 1–9, 1922.

An accurate classification of the unaltered porphyry is impossible. Ahlfeld [8] gives a chemical analysis of an altered rock, which he calls a dacite, but to judge from numerous thin sections, quartz is more abundant than in the average dacite, and biotite more common than in rhyolite. Assuming that both plagioclase and orthoclase were present in the groundmass, the rock would be classed as a quartz-latite porphyry.

Throughout large areas of the stock, the altered porphyry includes abundant sedimentary fragments, seldom more than one half inch in length, and distributed several inches apart throughout the igneous matrix. As the fragments become smaller and less numerous, the porphyry breccia grades into the quartz porphyry and contacts cannot be mapped accurately. On the upper mine levels, the area of breccia includes fully half of the stock, but in depth the proportion is less.

A coarse clastic breccia, highly mixed in character, forms irregular bodies along the margin of the stock, and well within its border. The fragments, up to several feet in size, are generally porphyry, and the matrix is black, highly altered, clastic material, which in thin section is similar to the sericitic quartzite. The breccia may continue for 100 feet or more along a drift or it may form block-like bodies, dike-like masses, or the merest pencil-line streaks in the white porphyry. The sedimentary rocks of the breccia appear to be of local derivation, and the white and gray porphyry fragments show but little variation.

Black clastic dikes cut the white porphyry, and they are made up of material similar to the matrix of the coarse breccia. On casual observation, they suggest basaltic dikes, but examination with a hand lens reveals their clastic texture, and the microscope confirms their non-igneous origin; that is, that they are not congealed magma. The dikes vary from an inch to three feet in thickness; some persist for several hundred feet, but others soon pinch out completely or merge with irregular masses of clastic breccia. As observed under the microscope, the quartz grains of the dikes are comparable in size and form with those of the quartz-

[8] Ahlfeld, Friedrich: The Tin Ores of Uncia-Llallagua, Bolivia. ECON. GEOL., vol. 26, p. 243, 1931.

ite, and not with the phenocrysts of the porphyry. The matrix is almost universally altered, and tourmaline is the principal product. A few rounded zircons prove transportation and wear.

The clastic dikes are of uncertain origin, but they are closely related in space to the clastic breccias, and the two probably formed in much the same way. They may represent ground-up rock material forced upward as "intrusive mud," or they may be fragmental material and volcanic sediment which have filtered in from above. Somewhat similar rock bodies have been recorded in the Tertiary eruptives of Nagyag, and Verespatak, Hungary.[9]

The Late Tertiary Volcanics.—Many of the ridges north of the Salvadora stock are capped by a volcanic formation, which can be traced nearly to Oruro, although it is rarely more than 100 feet thick.[10] The formation is distinctly faulted, but it is only slightly tilted and rests in nearly horizontal position on the folded sedimentary series. It is variously described as andesite and rhyolite, and that near Llallagua is probably a rhyolite tuff. Most writers agree that the volcanics are later in age than the tin mineralization, but thus far no ore bodies have been discovered beneath the volcanics.

Hot Springs.—Several hot springs occur in the vicinity of Llallagua. The sinters of the Uncia springs, according to Lindgren,[11] consist mainly of calcareous tufa, with lenses of opal, manganese dioxide, and barite. Of special interest is the small quantity of tungsten associated with the manganese. There is no tin or gold. The springs are located about three miles southeast of the Salvadora stock.

STRUCTURAL GEOLOGY OF THE VEINS.

The Llallagua veins differ greatly in width, persistence, and structural detail, but, broadly considered, they possess a certain

[9] Beck, Richard: The Nature of Ore Deposits, pp. 315, 318. Trans. by W. H. Weed, New York, 1909.

[10] Kittle, Erwin: Revista Minera de Bolivia, vol. 2, pp. 51–52, 1927. Ahlfeld, Friedrich: Neues Jahrb. f. Min. u. s. w. Beil., Bd. 65–A, 1932, Plate 50.

[11] Lindgren, Waldemar: A Recent Deposit of a Thermal Spring in Bolivia. ECON. GEOL., vol. 17, pp. 201–206, 1922.

pattern, which is revealed principally by the interrelations of two vein types. Where mineralization has followed strong, persistent fractures, it has formed veins of major importance, but where it has been controlled by numerous small cracks, the result is a maze of small veins, which are individually difficult to follow. The principal veins of the mine, as developed on a typical level, are illustrated in Fig. 1.

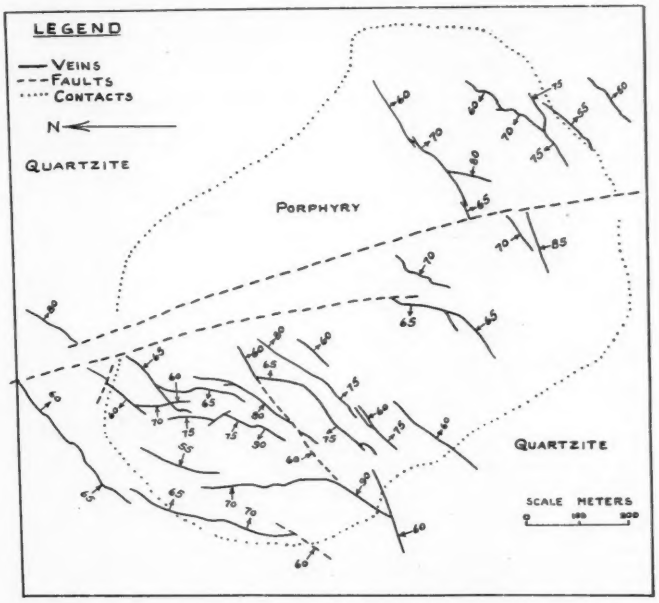


FIG. 1. Generalized plan of the principal veins as developed on a typical level.

Fracturing has been more intense within and contiguous to the quartz porphyry, but some of the larger structures can be traced far beyond the contact, and the veins maintain a general parallelism over an area considerably greater than that of the stock.

Pre-Mineral Fracturing.—The veins are roughly parallel, with northeasterly trend, but each major vein is interrupted by short

segments which diverge as much as 60° from the average strike of the vein. The ore commonly extends around the angles and along the segments of abnormal strike, thus indicating a complex system of pre-mineral fractures, rather than offsets by post-mineral faults.

Pre-mineral fracturing is clearly illustrated in Fig. 2; the stoped vein shows an abrupt change in strike, but detailed mapping reveals barren clays as the southeasterly continuation of one segment and pyritic seams as the northeasterly continuation of the other. Thus, the relation is in reality that of two intersecting

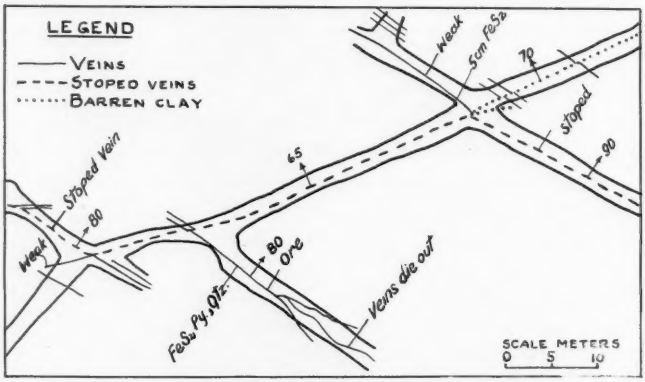


FIG. 2. Pre-mineral fracture pattern. Note development of two sets of fractures, and ore following both.

fractures, and the mineralization passes abruptly from one fracture into the other. Figure 3 illustrates the same feature although the vein structure is highly complex in detail.

At certain local points one veinlet may intersect another with slight offset, but this relationship cannot be extended to any group of veins, and the fractures were formed during a single, but somewhat extended, period of stress. Rock failure largely preceded ore-deposition, but probably some fractures were being formed while others were being filled, and certain faults prove post-mineral adjustments under stress. However, the field relations defi-

nitely preclude any conception of stages in mineralization separated by periods of strong earth movement; vein filling was a continuous process, with minor pulsations but without well-defined breaks.

Strike and Dip.—The majority of veins strike from north to N. 45° E., but a few strike from N. 50° E. to N. 80° E. and nearly every large vein includes sections of abnormal strike, not

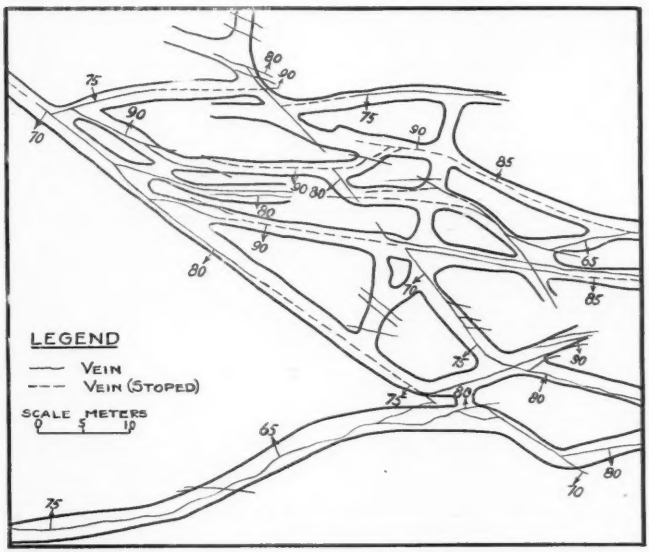


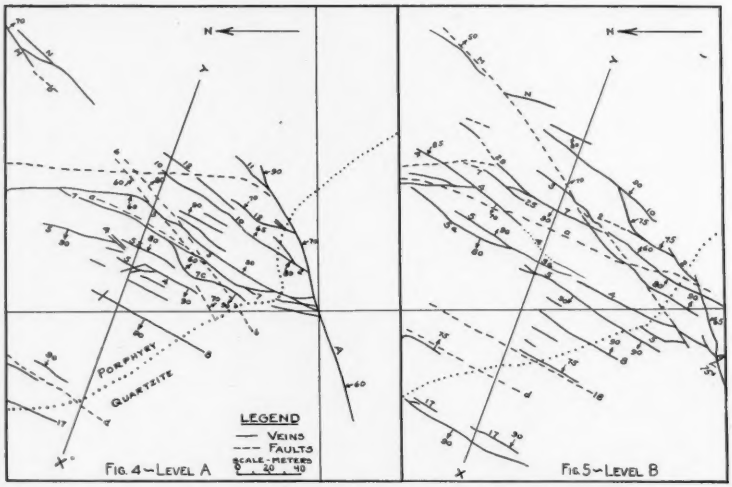
FIG. 3. Pre-mineral fracture pattern somewhat more complex than that of Fig. 2.

uncommonly N. 70° E. or N. 20° W. The stronger veins generally dip from 60° to 75° either to the east or west, but approximately vertical veins of a less persistent character occur throughout the mine.

The Two Vein Types.—A detailed study of vein structure indicates that there are two distinct vein types, here referred to as the San Jose type and the Serrano type. A single vein seldom

exhibits all distinguishing features, and the two types are not as definite as might be implied from the description that follows.

The larger veins, and nearly all those worked in former years, are of the San Jose type, characterized by a dip of 45° to 75°, heavy to moderate clay gouge, good width, and persistence. They have accounted for many ore-shoots of bonanza value, including the famous San Fermin-San Jose shoot, which was perhaps the largest shoot of high-grade tin ore ever mined. The veins aver-



FIGS. 4, 5. Typical Serrano vein structure as developed on two contiguous levels.

age about two feet in width, but stopes six feet wide are not uncommon. Veins of this class are marked by abrupt changes in strike, but a general trend is maintained over long distances, and when once encountered their further development offers little difficulty.

The typical Serrano veins show widths of a foot or less, little if any clay gouge, and nearly vertical dip. They are far less persistent than the San Jose veins, and they soon break up, feather

out, or join other veins both in dip and strike. Individuals can rarely be traced more than 200 feet, but in places they present a crude *en echelon* arrangement, and elsewhere, taken together, they form a mineralized zone which can be projected with some confidence.

Within a limited area, the Serrano veins show an approximate parallelism, but mineralization along less persistent cross-fractures

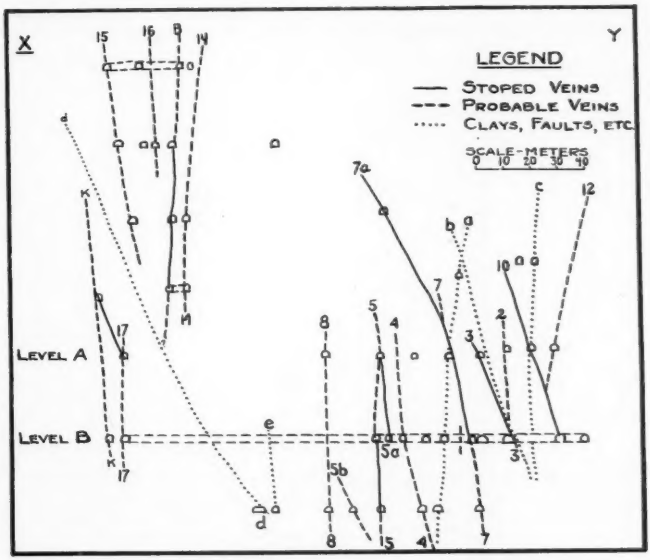


FIG. 6. Cross-section X–Y of Figs. 4, 5. Typical Serrano structure.

and others of low dip adds to the complexity of the vein pattern and causes a marked contrast in the arrangement of drifts on contiguous levels (Figs. 4 and 5). The difference between this type of fracturing and that of the San Jose type is more clearly evident in vertical section (Figs. 6 and 7).

Veins of the Serrano type are particularly abundant in certain areas. They form branches of the San Jose veins, especially in the hanging wall, connecting elements between the larger veins,

and essentially independent structures. The lateral change from one type of mineralization to the other is illustrated in Fig. 8.

Many Serrano veins are as rich as those of the San Jose, but due to the narrow width of the vein, dilution with low-grade wall rock is unavoidable, and the grade of ore is correspondingly reduced. Nevertheless, the Serrano veins may be so closely spaced that they form a single stope from 15 to 35 feet wide, or a series of stopes 10 to 20 feet apart; and a given block of ground with mineralization of this type may contain far more ore than another of equal size with mineralization confined to a single vein of the

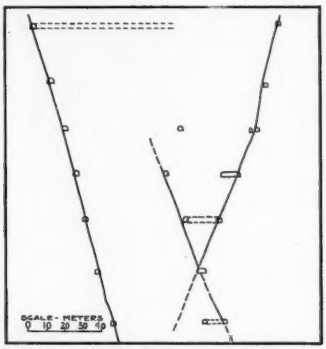


FIG. 7. Mineralization confined to strong veins of the San Jose type. Compare Fig. 6.

San Jose type. In former years the smaller veins did not receive much attention, but to-day they are being actively developed, and they add materially to the ore reserves.

Post-Mineral Faults.—The faults that cut through the central part of the mineralized zone record important post-mineral displacement, and others of local character show offsets from a few inches to a few feet. Some which are approximately parallel to the San Jose veins may reflect continued stress of the type that formed the San Jose fractures, and the fact that the larger faults are parallel to short N. 20° W. segments of the stronger veins

may imply that both veins and faults were developed during a single prolonged period of stress.

Origin of the Fracture Pattern.—The fractures, veins, and faults, in reality, define a strain pattern which can be studied in the field; but the major stresses can be inferred only from an analysis of the pattern, backed to a degree by laboratory experiment.

The San Jose veins are persistent and of low dip, and in places they are marked by tough gouge, slickensides, and brecciation;

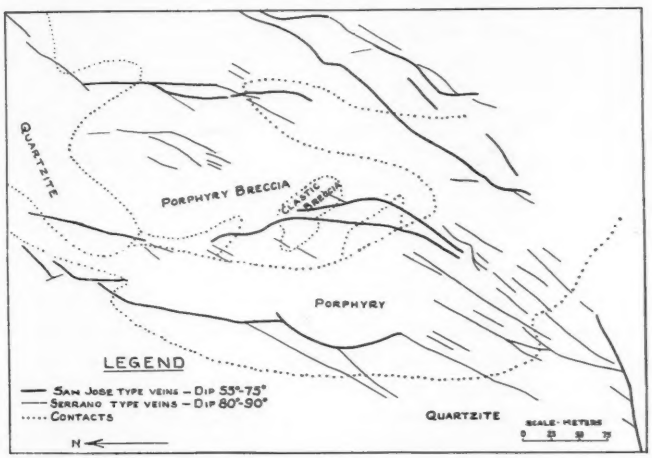


FIG. 8. Vein Types, Level C.

details which point to shearing stress of some nature. The Serrano veins, on the other hand, show nearly vertical dip, non-persistent habit, and tight filling; features which suggest development under tension.

The Llallagua vein pattern is probably not related to the Salvadora intrusive alone but is more regional in character. It is distinct from the vein system of Zinnwald, Saxony,[12] which includes two sets of veins, one nearly vertical and at right angles

12 Beck, Richard: *Op. cit.*, pp. 164, 203–207.

to the granite contact, and the other dipping at low angles, approximately parallel to the flat granite surface. These fractures have been assigned to stresses set up by the cooling of the granite at Zinnwald. The Llallagua veins, on the other hand, suggest the Butte system on a small scale, or the lattice developed in the laboratory under progressive shearing stress. In this latter connection, the experimental work of Mead is highly suggestive. After coating a horizontal sheet of rubber with paraffine, he subjected the system to progressive shearing stress, and fractures developed in the paraffine layer, as follows:

> The first fractures to appear at any one locality on the rubber sheet are usually tension cracks inclined about 45° to the direction of shearing movement. These are at right angles to the direction of maximum elongation and appear as vertical open cracks. They are followed immediately by two sets of vertical faults with horizontal displacement, one set striking parallel to the direction of movement and the other parallel to the free edges of the rubber sheet. These represent two directions of non-distortion, or two shear planes developed by the shearing movement in which direction of relief is in the plane of the paraffine layer.[18]

The experiment is essentially an application of the principles of mechanics to the failure of brittle material under simple shearing stress; the planes of maximum shear are parallel to the stress, at 45° to the direction of maximum tension, and at 45° to the direction of maximum compression. In Mead's experiment only two fractures related to compression were developed, in contrast to the countless fractures of simple shear and tension. They assumed the form of "thrust faults striking approximately at right angles to the tension cracks and inclined approximately 45°, dipping in either direction."

Considering the Llallagua pattern in the light of these experiments, the veins of the San Jose type may include two groups, one striking N. 70° E. and the other N. 20° E. The two differ not so much in structural detail as in persistence, and, recalling typical exposures in the mine, it is believed that the N. 70° E. group is the stronger, with more evidence of movement. Veins of this

[18] Mead, W. J.: Notes on the Mechanics of Geologic Structures. Jour. Geol., vol. 28, pp. 512–513, 1920.

class may constitute the major frame-work of the fracture pattern, to be compared with the shear planes of the experiment, which were developed by a shearing force acting parallel to their trend. Typical veins of the N. 70° E. group are indicated, therefore, as S_1 planes in the idealized diagram of Fig. 9, whereas other veins of the San Jose type, of more obscure origin, are designated as X veins.

The Serrano-type veins are almost certainly due to tension, and they are indicated as T veins in the diagram. Theoretically they

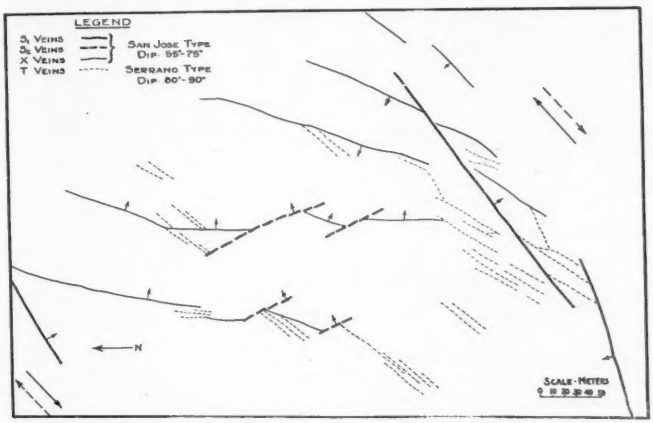


FIG. 9. Idealized plan of a part of the vein system.

should diverge from the S_1 elements at an angle of 45°, and this is roughly in accord with their position in plan. Tension failure in this direction implies a shearing couple acting in the direction of the solid arrows, but this orientation places the X veins approximately perpendicular to the direction of tension; a fact difficult to correlate with their low dip and clay selvage. Possibly they reflect displacement of a minor nature, due to the gravitative settling of the blocks after the fractures were first formed under tension.

Instead of being due to tension, the X veins may be due to com-

pression acting at right angles to their trend, with the relief of stress taking place by some blocks moving upward with respect to others, accompanied by shearing failure along the X planes. The latter would then be comparable with the minor thrust faults of the laboratory experiment, and they would require a shearing

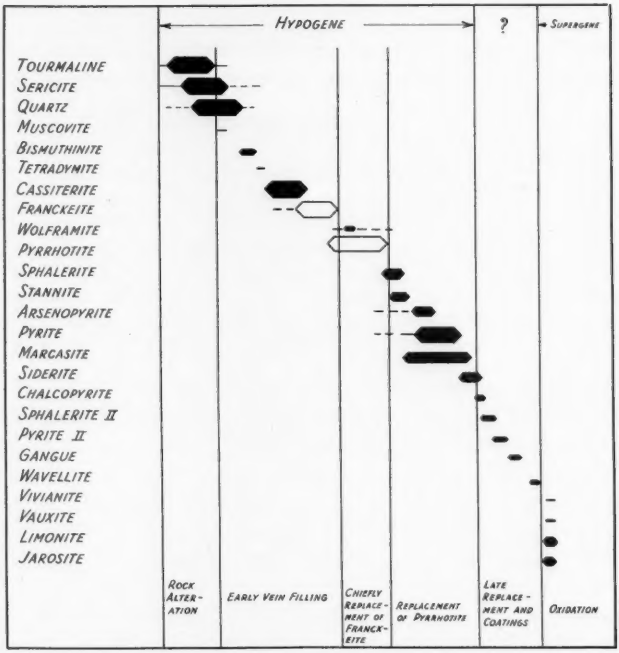


FIG. 10. Graphical representation of mineral sequence.

couple acting in the direction of the dotted arrows; that is, opposite to that of the previous hypothesis. The X veins are perhaps more reasonably explained in this way, but not the T veins, which, although of the tension type, are now nearly parallel to the assumed direction of compression failure.

In the experiment, a second group of shear planes developed at

right angles to the first; but at Llallagua such structures are poorly developed, with the exception of short segments of the major veins, and the major central faults (S_2 elements of Fig. 9). These structures have the required strike (N. 20° W.), and they may form an essential part of the fracture pattern, representing a zone of failure complementary to the S_1 direction of shear, but somewhat later in final development. On the other hand, the faults involve post-mineral displacement, and they may be of much later and of independent origin.

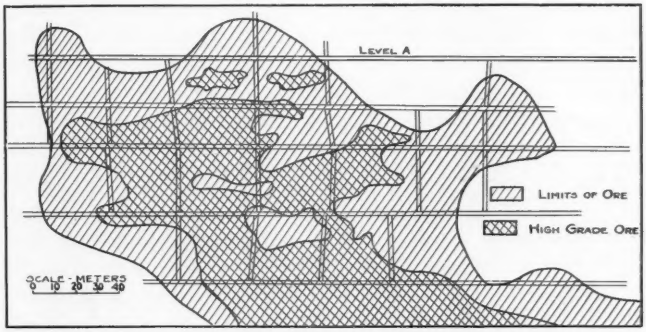


FIG. 11. Longitudinal section of vein to illustrate the occurrence of high-grade ore within the larger ore-shoot.

Both stress hypotheses suggested are open to serious criticism; the X veins are difficult to correlate with the first, and the T veins with the second. In many details, the field relations do not correspond with the theory; the S_1 veins are not vertical but dip at low angles in either direction, both the S_1 and X veins are marked by abrupt changes in strike which would seem to deny important lateral displacement, and the T veins are locally parallel to the X veins.

In view of these differences, it may be questioned whether a theoretical analysis of the kind attempted is of value; but shearing stress in nature seldom acts in a horizontal plane, and if the shearing couple were inclined, or if torsional stresses were in-

volved, the resulting strain pattern would be extremely complex and difficult to analyze. Nevertheless, the Llallagua fracture pattern, like that developed in the laboratory under progressive shearing stress, includes two or more types of fractures, which contrast in structural detail but are of essentially the same age; and the general similarity between the two patterns compels the belief that the Llallagua veins were developed by shearing stresses of a regional character rather than by stresses localized within the

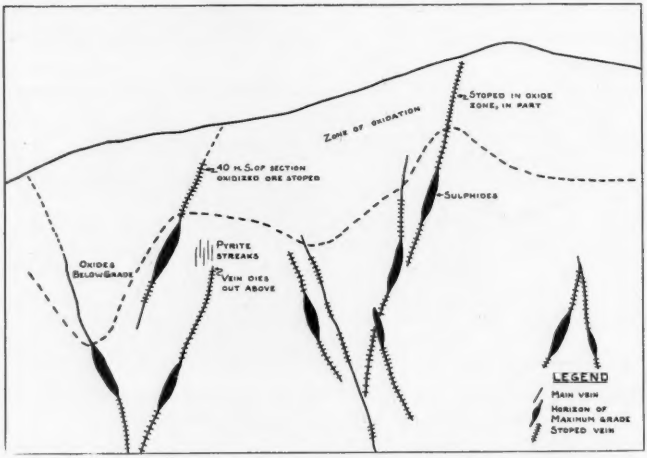


FIG. 12. Generalized cross-section showing the high-grade ore horizons.

intrusive. The Llallagua formations represent a non-homogeneous system, and this variation in physical character may account for the greater intensity of fracturing within and close to the Salvadora stock.

HYDROTHERMAL METAMORPHISM.

Hydrothermal metamorphism is but a part of the larger process of mineralization which, in the Llallagua district, has had two results: one, the widespread alteration of the stock, and the other, the deposition of ore minerals. One forms valueless altered

rocks; the other, tin ores among the richest known. Both represent overlapping episodes in a continuous process; but rock alteration, as will be shown presently, began before ore deposition and was directed, in part, by channelways which antedate the veins.

Mineralogy of the Altered Rocks.—The unaltered porphyry was probably a silicic type closely related to rhyolite or quartz latite, but is not composed almost wholly of residual and secondary quartz, sericite, and tourmaline, with minor quantities of rutile, cassiterite, and zircon.

Tourmaline occurs in nearly every thin section. Under the microscope it is almost colorless, but in some cases exhibits distinct pleochroism in light shades of green and brown. Examination by immersion methods gave $\epsilon = 1.625$ and $\omega = 1.645$, indicating a variety low in iron and one probably close to dravite.

In the sericitic groundmass of the typical porphyry, the tourmaline forms scattered grains and fine aggregates interspersed with needles; in the replacement of feldspar phenocrysts it develops in coarse plates and rosettes up to 1.5 mm. across; and in the highly altered porphyry it forms the groundmass and corrodes the quartz phenocrysts as well. Some thin sections reveal a selectivity in replacement; tourmaline favors the biotite, sericite the feldspar, and quartz the groundmass.

Tourmaline alteration is even more characteristic of the clastic dikes and breccias. It forms from 40 to 90 per cent. of the matrix, completely replacing the finer material, and invading the larger quartz grains as long needles and irregular aggregates.

Sericite is the most abundant and widespread metasomatic mineral. In the groundmass of the typical porphyry, it occurs as a fine-grained fibrous mat, but as an alteration of feldspar phenocrysts it may simulate a lattice arrangement, and as a replacement of biotite it may be moderately coarse. In specimens of the argillaceous quartzite distant from the veins, the sericite forms scattered shreds in the matrix, but in specimens from the ore zone, it is more abundant and replaces the quartz.

The amount of secondary quartz in the altered porphyry is difficult to estimate, but some types are highly silicified, with a

groundmass made up of closely interlocking quartz grains from 0.1 to 0.2 mm. in size. Where the major veins occur in quartzite, the vein walls may be so thoroughly silicified as to merge with the quartz of the vein filling.

Rutile is a minor constituent of the altered porphyry, most abundant in the corroded phenocrysts of biotite where, in typical crystal form, it is arranged parallel to the biotite cleavage. Most rutile represents titanium that has been rejected in the alteration of biotite, but scattered grains in the porphyry groundmass and in the sediments suggest that some titanium has been added by the hydrothermal solutions.

A number of thin sections include blunt crystals, grains, and small patches of cassiterite, and a few show fibrous and granular cassiterite as a partial pseudomorph after biotite (Fig. 13). Truly disseminated ore is not characteristic of the deposit. Chlorite is apparently limited to the marginal dikes as an alteration of the ferro-magnesian minerals. Siderite was identified in one specimen of shaly sandstone, and zircon in several of quartzite and porphyry. A careful search was made for apatite, but none was found.

Distribution of the Altered Rocks.—Sericitized porphyry describes the great body of the Salvadora stock. Alteration is independent of major fractures, of veins, and of contacts; it represents a permeation of the whole rock mass, and a penetration so effective that scarcely a phenocryst has escaped attack.

Highly tourmalinized porphyry has been referred to in the field as "black porphyry." It forms small irregular masses, large bodies extending 100 feet or more from the veins, and narrow belts parallel to fractures which may or may not contain cassiterite. The black porphyry, the clastic breccias, and the clastic dikes, rocks which consist largely of tourmaline, occur throughout the ore deposit, thus indicating a lack of vertical zoning of tourmaline.

Highly silicified porphyry, dense and of a light gray color, occurs locally as a narrow band along the veins, and its development was closely associated with vein formation.

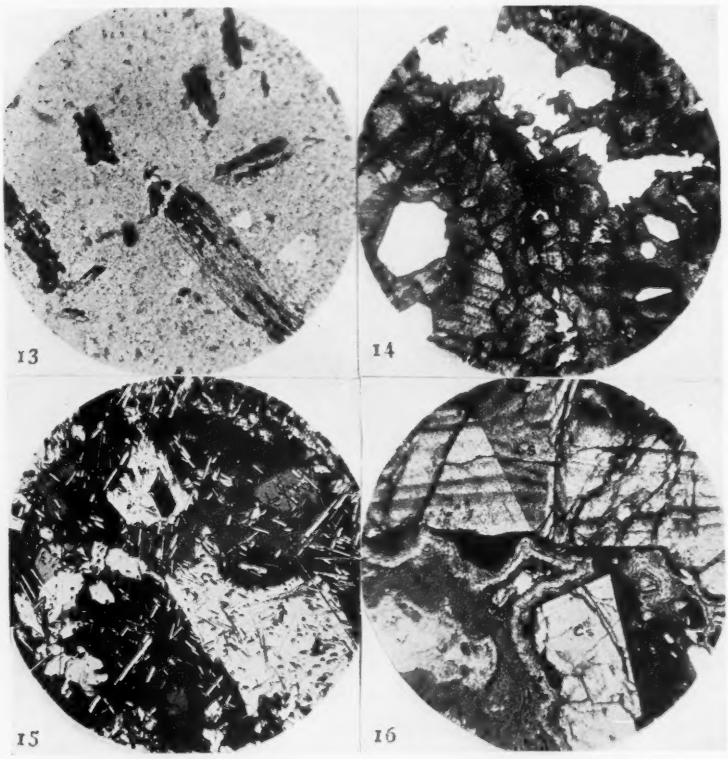


FIG. 13. Sericitized porphyry with biotite plates replaced by tourmaline and cassiterite. Forastera vein, 700 level. × 32.

FIG. 14. Cassiterite (black) corroding euhedral quartz (white) and muscovite (white, fibrous). Salvadora vein, 800 level. Thin section, × 35.

FIG. 15. Tourmaline needles scattered through vein quartz. Bismarck vein, 1150 level. Crossed nicols, × 60.

FIG. 16. Cassiterite (*Cs*) of the oxide zone, showing color banding. Cassiterite coated with jarosite and other oxidation products. Blanca vein, 900 level. Thin section, × 32.

The Sequence of Events.—The clastic dikes and breccias are distinctly cut by the cassiterite veins; they are heavily tourmalinized, and yet seldom contain ore. The black porphyry forms large areas independent of the veins, and narrow bands parallel to fractures which may be barren of ore. Thus hydrothermal metamorphism, with the deposition of tourmaline, began before the vein fractures were formed, and it was directed by channelways of earlier development, especially by the irregular zones of breccia and the clastic dikes. However, tourmaline deposition continued, and needles were deposited in the early vein quartz, indicating a slight overlap of the two minerals. Most sericite aggregates show no distinct age relation, but the clastic dikes contain very little sericite, and perhaps they were effectively sealed with tourmaline before sericite deposition began.

In summary: Hydrothermal metamorphism at Llallagua involved the abundant deposition of low-iron tourmaline, sericite, and quartz. Alteration of the stock was already in progress when the fractures were formed, and tourmalinization largely preceded vein formation. There is no clear-cut relation between tourmaline and cassiterite, although both are abundant; the one in the wall rock, the other in the veins.

GENERAL DESCRIPTION OF THE ORE DEPOSIT.

Area of Mineralization.—In early years, some silver is said to have been produced at Llallagua, but the ore mined to-day carries tin without silver. The area of tin mineralization is roughly comparable in size with that of the Salvadora stock, but the two are not coincident, and high-grade ore has been produced from veins wholly within the sediments.

A "pyritic" zone broadly surrounds the principal tin area, but the intervening boundary is vague and subject to modification as development progresses. Hypogene zoning thus exists in the district, and is expressed mainly by the distribution of cassiterite.

The "Lodes."—In describing the Llallagua fracture pattern, the veins were referred to as units; but, as a rule, they consist of several mineralized fractures and small cracks, or more rarely

sheeted zones, rather than a single streak of ore. In the strict sense of the term, they are lodes rather than veins. The typical high-grade face includes two or three veinlets, each from four to ten inches in width, but some of phenomenal value present a single vein from two to three feet wide, composed almost entirely of cassiterite. In many places the wall rock shows tin on assay, but most of the cassiterite occurs as minute fracture fillings rather than in disseminated form.

Ore-shoots.—Some of the smaller veins are mined throughout their length as mappable units, but the major veins show large lens-like ore-shoots which terminate at "assay limits," or less commonly at vein junctions, post-mineral faults, or formation contacts. Some veins continue well beyond the limits of ore, but others soon pass into sheeted zones or tight clay seams with little if any mineralization. Certain parts of the larger shoots are very high grade, and they form the "bonanza shoots" to be described later.

The Vein Filling.—For the most part the lodes represent the filling of fractures. The veins are sharply defined, crustified, and drusy; and the ore, on a microscopic scale, is highly porous. Evidences of ore replacement are notably absent at Llallagua. The mineralogy of the altered wallrock contrasts with that of the vein filling.

Cassiterite, quartz, pyrite, and marcasite make up perhaps 90 per cent. of the vein filling. Arsenopyrite, bismuthinite, pyrrhotite, and wolframite predominate in a few places, and any one of several minerals may be conspicuous in carefully selected hand specimens: stannite, franckeite, siderite, apatite, wavellite, or vauxite.

As described in detail on a later page, franckeite and pyrrhotite were abundant at an early stage of vein formation, and they formed the principal filling of many veins now composed of pyrite and marcasite. The early and almost complete elimination of franckeite by hypogene solutions was accompanied by a decided loss in tin, thus affording a pronounced example of "hypogene impoverishment." No cassiterite of later deposition is

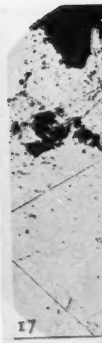
found, and nearly all the tin was carried upward beyond the present ore-bodies.

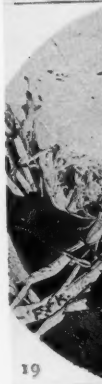
A banded filling is typical of many medium-grade veins from four to ten inches in width. It is not the delicate, repeated banding characteristic of some Bolivian deposits, but is, none the less, distinct. Quartz is commonly attached to the vein walls, cassiterite forms two definite bands contiguous to the quartz, and iron sulphides make up the central streak; a broad sequence of deposition which is confirmed by the microscope. Accessory franckeite, stannite, sphalerite, and siderite generally occur with the iron sulphides.

THE VEIN MINERALS AND THEIR PARAGENESIS.

The laboratory investigation of the Llallagua ore offers evidence in support of the principal conclusions formulated in the field, and at the same time brings out many details of mineral relationship not otherwise suspected. The textures of the ore are highly complex and unlike those described from other localities, due to the extreme susceptibility to attack of two early soft minerals, franckeite and pyrrhotite, and to their almost complete elimination by hypogene solutions. Furthermore, certain sulphides which have replaced pyrrhotite, possess a structure which is probably inherited from the earlier franckeite. As a result, abnormal patterns, pseudomorphs, and antecedent veinlets abound, whereas many of the usual criteria of sequence are absent.

Summary.—In view of the complexity of mineral relationship, a summary of the sequence is presented here, to be followed by a detailed explanation of the textures, and a description of the minerals in their approximate order of deposition. The ores do not show a well-defined sequence, with each mineral clearly following another, but instead, several gradational episodes of vein formation, following upon and coincident with the widespread alteration of the Salvadora stock: (1) vein filling of quartz, bismuthinite, cassiterite, and franckeite, (2) replacement of franckeite by pyrrhotite, (3) replacement of pyrrhotite by wolframite (?), stannite-sphalerite, marcasite, arsenopyrite, pyrite,





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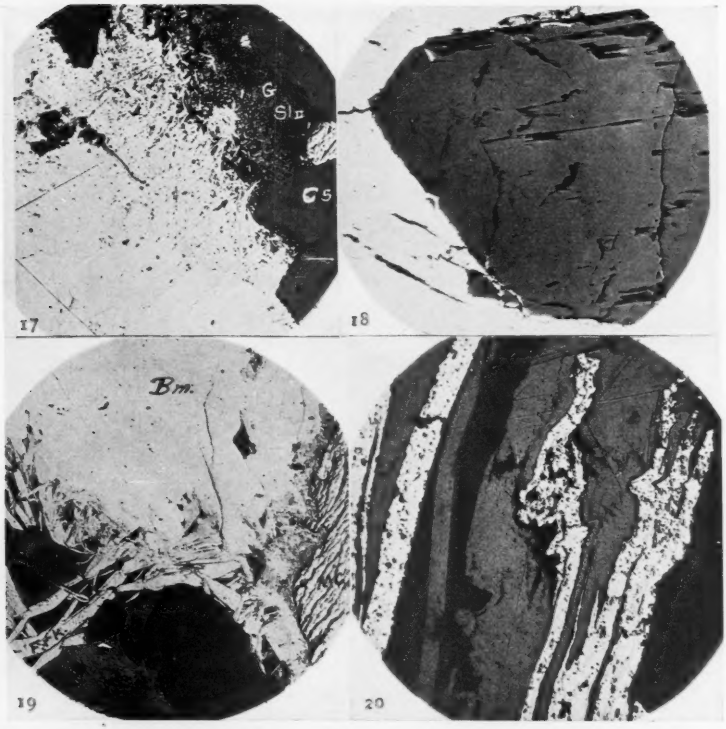


FIG. 17. Typical alteration of bismuthinite. The fibrous alteration products include gangue (*G*) with some late sphalerite (*Sl–II*). Cassiterite grain (*Cs*) corroded (?) by bismuthinite. Small angular patch of tetradymite (white) in the bismuthinite. Latter shows two shades due to different orientation of plates (Bm–1, Bm–2). Contacto vein, 1500 level. × 80.

FIG. 18. Euhedral cassiterite, with solution pits and fractures partly filled with marcasite and pyrite. Polished section. Contacto vein, 1500 level. × 80.

FIG. 19. Bismuthinite (*Bm*) bordered by franckeite with a platy habit (*Frk*), the latter partly surrounded by sphalerite II. A little marcasite (*Mc*). Animas vein, 1100 level. × 80.

FIG. 20. Marcasite-pyrite aggregate forming a pseudomorph after distorted franckeite (dark gray). Serrano vein, 1000 level. × 130.

and probably siderite, (4) crustification and subordinate replacement by sphalerite II, pyrite II, chalcopyrite, and gangue, (5) deposition of wavellite, and (6) supergene deposition of limonite, jarosite, hydrous iron phosphates, and covellite. The sequence is summarized graphically in Fig. 10.

The broad sequence of events is clear, but with the exception of the early vein filling, detailed relations are difficult to determine. In other Bolivian deposits, repeated deposition and overlap are clearly indicated by a delicate banding of the veins; but at Llallagua, where pseudomorphic textures prevail, the same history is recorded in a far more obscure way.

The principal replacement of pyrrhotite by lamellar marcasite, arsenopyrite, and pyrite is definitely hypogene, but possibly the "late sulphides" (4) and wavellite are supergene. The textures, however, reveal no well defined break between tourmaline and wavellite, and these two minerals probably represent the initial and final products of hypogene deposition.

Quartz.—Quartz is the principal accessory of the high-grade veins, and the predominant filling of many veins, especially in the lower mine levels; but it is relatively subordinate in the low-grade pyritic veins. In some thin sections, the quartz is highly corroded; in others, it is euhedral, although surrounded by later minerals, particularly by cassiterite or iron sulphides (Fig. 14). Stannite rarely forms a pseudomorph after quartz.

Tourmaline.—Tourmaline occurs principally as a metasomatic mineral of early age, but lance-like units, rods, and grains appear in the vein quartz. Some represent corroded remnants of larger rosettes, but others, scattered at random through the quartz, can hardly be explained in this way but suggest some continued deposition of tourmaline after quartz (Fig. 15).

Bismuthinite.—Bismuthinite is a minor constituent in some high-grade veins but absent in others. It forms imperfect radiating groups and lance-like individuals up to 5 centimeters in length.

Under the microscope, the bismuthinite is commonly surrounded by granular cassiterite. Some units are highly corroded, but a few rounded cassiterite crystals suggest a slight

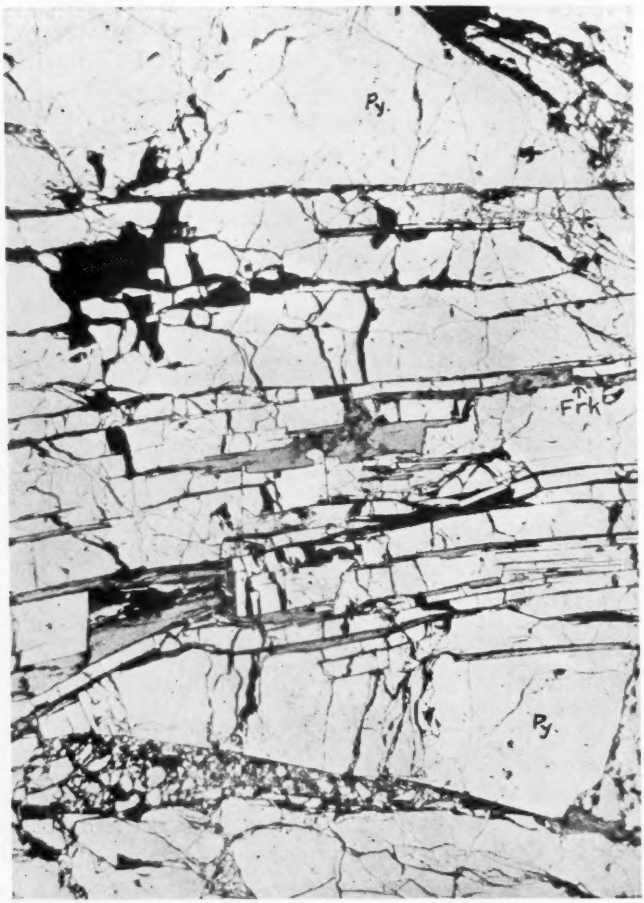


FIG. 21. Pyrite (*Py*) of massive texture forming a pseudomorph after distorted plates of franckeite (*Frk*). Crucero vein, 1200 level. ×230.

overlap of the two minerals (Fig. 17). Bismuthinite, in contrast to franckeite, is not largely replaced by the later base-metal sulphides, although it does show a characteristic and common alteration. At first, the mineral cleavage is accentuated, then the laths are transformed into fibrous aggregates, and finally the mineral persists only as scattered shreds in the alteration product. The latter consists largely of dark gangue too fine in grain for identification, but locally it includes sphalerite II and chalcopyrite (Fig. 17). The alteration may be an oxidation process, as suggested by Ahlfeld,[14] but evidence discussed elsewhere indicates that sphalerite II and chalcopyrite are probably hypogene.

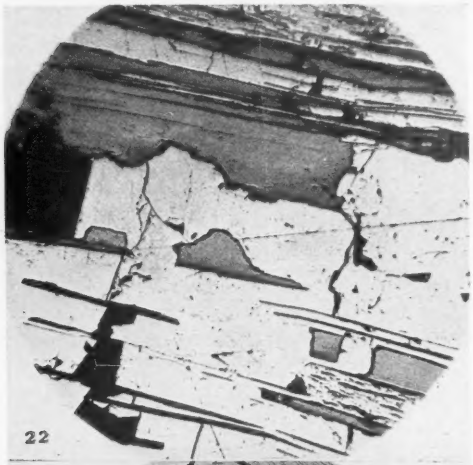
Cassiterite.—Cassiterite is the only ore mineral of Llallagua, and many high-grade veins show a filling of cassiterite and little else. Cassiterite also occurs in the banded ores and in countless "pyritic" veins of low grade.

Megascopically the cassiterite is nearly black in color, loosely granular to compact, fine to medium grained, and crystalline. In thin section, it is brown to light yellow with distinct color banding (Fig. 16). Individual crystals measure up to a centimeter across; some are sharply euhedral, others deeply corroded. The solution cavities, enlarged contacts, and fractures are commonly filled with pyrite or marcasite; and although this represents a solution of tin, it bears no relation whatever to supergene enrichment (Fig. 18). A few thin sections include radiating fibrous cassiterite, but it is associated with cassiterite of normal character, and both types are definitely hypogene.

Disseminated ore is not common at Llallagua, but locally a black rock, which may be altered porphyry, carries good tin values. As observed in thin section, the rock consists of tourmaline and cassiterite, both of which are probably of replacement origin; but the original material has been so thoroughly altered as to escape recognition. The cassiterite corrodes the tourmaline and fills the space between the tourmaline laths.

Cassiterite is later than quartz in nearly every banded vein, but the two minerals are closely associated; and, in rare examples, the

[14] *Op. cit.*, p. 251.



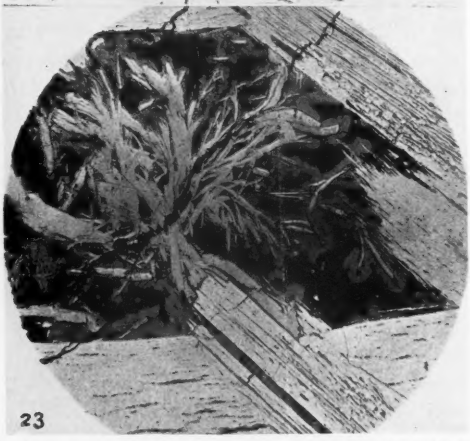


FIG. 22. Franckeite laths deeply corroded by pyrite, which locally retains the franckeite texture. Small area of marcasite (white, lamellar). Contacto vein, 1000 level. × 70.

FIG. 23. Marcasite pseudomorphs outlining original laths of franckeite. Franckeite (light gray) forms residual fibers which pass into a feathery, distorted aggregate. Latter is coated by sphalerite II (dark gray), and then by gangue (black), which forms a thin layer; most of the interstitial material is bakelite. Salvadora vein, 800 level. × 55.

cassiterite bands are followed by quartz. Most of the bismuthinite is earlier than cassiterite, but pyrite and other common sulphides are definitely later (Fig. 18). No subsequent generation of cassiterite is recorded, and no evidence of a supergene deposition. Traced into the oxide zone, it shows the same sharp borders, crystal faces, and granular aggregates which are so characteristic of the sulphide zone. Typical oxidized ore includes residual, unaltered cassiterite, "limonite," jarosite, and clay. The minerals of the oxide zone may form a cement for the granular cassiterite, they may widen and force their way into small fractures, or they may form coatings; but they do not replace the cassiterite, which has successfully withstood supergene attack (Fig. 16). Berkey and Colony [15] made a microscopic examination of the Llallagua ore some years ago and came to the same conclusion.

Franckeite.—Franckeite was an important constituent at an earlier stage of vein formation, and it has undeniably left its stamp on the later mineral aggregate. Pseudomorphic patterns outline original franckeite laths up to several centimeters in length, but the mineral now occurs only as an uncommon accessory interlaminated with marcasite, or as a microscopic constituent, in scattered shreds, plumose aggregates, and acicular residuals, reaching in one polished specimen a maximum of some ten per cent.

Franckeite is characterized by low hardness, platy habit, and micaceous cleavage. It is somewhat similar to bismuthinite in polished section, but microchemical tests yield positive identification. Under geologically slight pressure, the plate-like units become deformed, from slightly bent to highly distorted, a fact of major significance in tracing the origin of certain textures (Fig. 20).

The Llallagua franckeite is early, contrary to the general rule that soft minerals, and especially lead-antimony sulphides, are late. In the banded veins, the franckeite occurs in the central

[15] Berkey, C. P., and Colony, R. J.: Private Report to Patiño Mines and Enterprises Con. Inc. Referred to in Mining Journal (London), vol. 168, pp. 41–44, Jan. 25, 1930, Supplement.

"pyritic" filling, and is thus later than cassiterite and bismuthinite. The same sequence is suggested by franckeite bordering bismuthinite, although the two minerals are rarely in contact (Fig. 19).

Franckeite laths deeply corroded by pyrite, and twisted plates delicately reproduced by pyrite-marcasite aggregates form highly interesting textures, and they offer convincing evidence of the early age of franckeite (Figs. 20, 21). Similar abnormal patterns are found in other minerals to be described later.

The franckeite shows variable replacement; some laths are completely destroyed, some persist as pencil-line streaks in pyrrhotite, pyrite, and marcasite, and still others are scarcely attacked (Fig. 22). Although at an early stage the mineral was highly unstable, it resisted late solution, and minute shreds and distorted fibers have persisted, only to be coated by sphalerite II and gangue. At first sight, the feathery aggregates suggest a late crustification, but they are probably of residual origin, and some can be traced into lath-like units of typical association (Fig. 23).

Wolframite.—Wolframite is an accessory vein mineral. In some sections it appears to be closely associated with cassiterite, although of later age; in others it is entirely surrounded by sulphides and appears to form a part of the central filling. Some wolframite exhibits elongated outlines, step-like borders, and elongated pits that are not related to cleavage but probably to early franckeite which has been replaced. Wolframite is cut by veinlets of pyrite and marcasite, but its relation to pyrrhotite is not definitely known.

Pyrrhotite.—In most veins, the pyrrhotite has been entirely replaced except for microscopic residuals,[16] but in a few it persists as an abundant filling associated with pyrite, marcasite and accessory siderite. Such specimens constitute the principal evidence as to the late mineral sequence, and they are described in detail later. The pyrrhotite is cut by fractures bordered by marcasite and by complex veinlets of marcasite, arsenopyrite, and pyrite. Except in a few specimens, the pyrrhotite between the

[16] The widespread replacement of pyrrhotite by pyrite and marcasite is also recognized by Ahlfeld (*op. cit.*, pp. 235–254).

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[16] The widespread replacement of pyrrhotite by pyrite and marcasite is also recognized by Ahlfeld (*op. cit.*, pp. 235–254).

FIG. 24. Complex texture illustrating the late attack of pyrrhotite (*Po*). Pyrrhotite cut by complex veinlets of arsenopyrite (*Aspy*) and of pyrite (*Py*). Continued solution of the pyrrhotite has developed irregular cavities parallel to the veinlets, and has isolated an earlier crustification of sphalerite II (*Sl*). Black is open space. Reggis vein. × 45.

veinlets has been completely removed, leaving a highly cellular network texture (Fig. 24). Nevertheless, the former presence of pyrrhotite is indicated by irregular, angular, or rod-like inclusions in pyrite, and groups of such inclusions with parallel orientation outline original anhedra up to 3 mm. across.

Sphalerite and Stannite.—Generally sphalerite and stannite occur together, but sphalerite is the more abundant and in places the dominant vein filling, with a greater lateral range than cassiterite. The ore-mineral of Llallagua is cassiterite, but the mill heads for 1929, averaging 3.99 per cent total tin, showed 0.10 per cent "soluble tin" including both stannite and franckeite.

In polished section, the stannite is brownish gray except in contact with pyrrhotite, where it is greenish gray. In places it includes blebs of chalcopyrite, not of ex-solution origin, but distributed along minute veinlets of sphalerite II.[17] Stannite is of about the same age as sphalerite I, although some contacts suggest a control by the sphalerite cleavage. Both minerals follow franckeite. Together, they form elongated projections parallel to franckeite residuals and to marcasite with its inherited pattern (Fig. 25); and sphalerite is marked by parallel rectangular pits at an angle to its cleavage. Pyrrhotite may have been an intermediate product; but if so, stannite and sphalerite closely followed since they are found next to early minerals such as quartz and cassiterite. Both minerals are cut by veinlets of pyrite and marcasite; but no distinct sequence is indicated with wolframite or arsenopyrite.

Arsenopyrite.—Arsenopyrite forms the principal filling of some veins, especially in the lower mine levels, and it is a common microscopic constituent throughout the ore deposit. Small plates and grains are difficult to distinguish from marcasite, but they exhibit a pinkish rather than a bluish tint in ordinary light, and show a mosaic-granular rather than a lamellar texture.

Arsenopyrite is later than franckeite, and it shows angular outlines and pits, which, more common in other minerals, have been traced to the franckeite structure. Arsenopyrite veinlets defi-

[17] These blebs may be the "unmixing particles of chalcopyrite" referred to by Ahlfeld (*op. cit.*, p. 249).

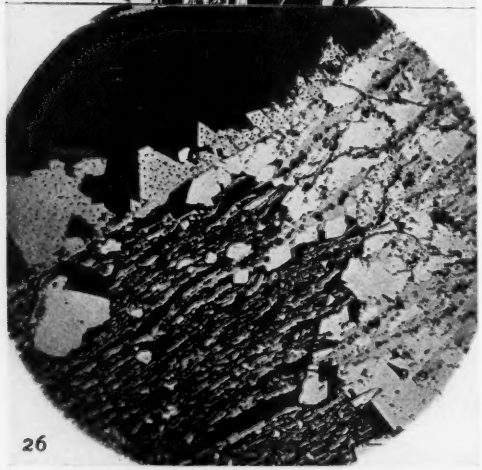


FIG. 25. Marcasite (white, lamellar) and pyrite (white, granular) pseudomorphic after franckeite (*Frk*), which persists as fibers surrounded by siderite (*Sd*). Sphalerite (*Sl*) and stannite (*St*) parallel the marcasite, showing franckeite control. Serrano vein, 1000 level. × 94.

FIG. 26. Marcasite, open lamellar, and dense, the latter associated with granular pyrite (white). Dots, arsenopyrite grains. The whole is an aggregate pseudomorphous after franckeite. Serrano vein, 1000 level. × 140.

nitely cut pyrrhotite, but some textures suggest a mutual boundary relation and an overlap in deposition (Fig. 31). In specimens from the lower mine levels which contain abundant arsenopyrite, the mineral boundaries are unrelated to the marcasite structure, and several arsenopyrite units show parallel extinction, thus indicating a replacement of arsenopyrite by pyrrhotite (now marcasite). The unique sequence between arsenopyrite, pyrite, and marcasite will be referred to presently.

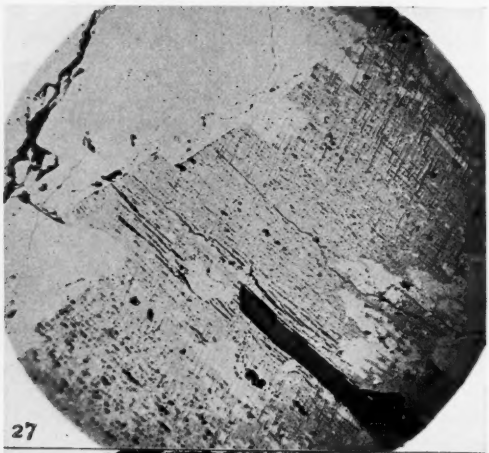
Marcasite Textures.—Marcasite and pyrite form scattered aggregates in veins composed principally of cassiterite and quartz; the central streak of banded ores; and the predominant filling of the low-grade "pyritic" veins, which occur both within and outside the zone of high-grade ore.

The iron sulphide identified without question as marcasite includes two varieties; a dense, fine-grained type, and an open, coarse-grained type. Under high power the former appears as a closely knit aggregate of irregular grains, and the latter as an open mosaic of lath-like units. Both show lamellar structure; in the one it is due to the shape of the inter-grain spaces, and in the other to the elongated form of both the grains and cavities. Both types are of common occurrence and persist to the deepest mine level (Figs. 26, 27, 29).

As already noted, some marcasite aggregates are delicate reproductions of interlocking or highly distorted laths of franckeite; and many marcasite areas contiguous to massive pyrite show step-like boundaries which can be traced to the franckeite cleavage (Figs. 20, 27). Broad bands of lamellar marcasite cut pyrrhotite, and these are continuous with similar bands next to early quartz, cassiterite, stannite, and sphalerite (Fig. 31).

Some of the Llallagua pyrite is slightly anisotropic, and some is minutely pitted and off-color. Ragged contacts suggest an alteration of pyrite to marcasite (Fig. 29); and one specimen includes a pyrite cube partly altered to marcasite. However, the specimens as a whole indicate that most marcasite has not been derived from pyrite.

In the pyritic filling, iron sulphide of very fine grain forms oval and irregular areas of concentric structure. Under high power,



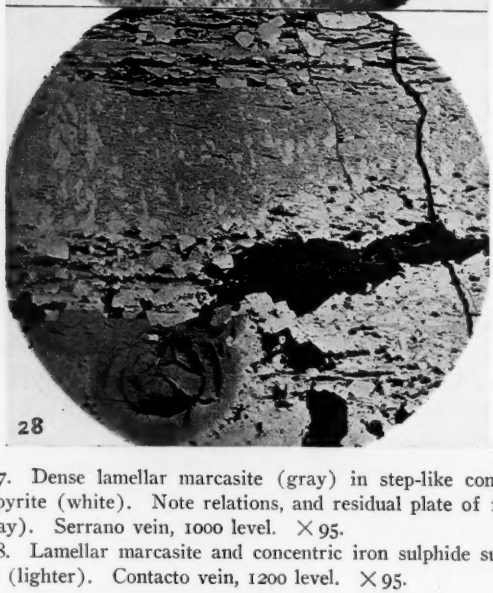


FIG. 27. Dense lamellar marcasite (gray) in step-like contact with massive pyrite (white). Note relations, and residual plate of franckeite (dark gray). Serrano vein, 1000 level. × 95.

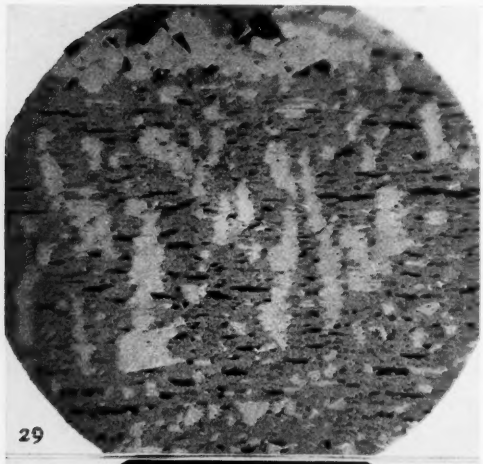
FIG. 28. Lamellar marcasite and concentric iron sulphide surrounded by pyrite (lighter). Contacto vein, 1200 level. × 95.

the material is slightly anisotropic; it is accordingly classified as marcasite, although the determination is somewhat uncertain. Pyrite is commonly associated with marcasite of this type, and it may fill the space between concentric bodies, as well as concentric and radial cracks. In places, the concentric sulphide surrounds cores composed of massive pyrite, lamellar marcasite, and arsenopyrite; elsewhere it extends outward from the lamellar marcasite bands (Fig. 28). Concentric marcasite probably represents an alteration of pyrrhotite, but it includes cavities of jagged outline in no way related to the concentric structure but probably patterned after early franckeite.

Pyrite Textures.—Some pyrite textures constitute perfect pseudomorphs after slightly distorted franckeite plates (Figs. 21, 22). More commonly the pyrite forms a granular aggregate of open texture, with pitted grains and angular inter-grain spaces; or a dense mosaic pattern with irregular and parallel cavities less closely spaced (Figs. 27, 28, 32).

Both the massive and granular pyrite contain abundant inclusions of pyrrhotite in the form of irregular patches and parallel rods. The inclusions are highly significant, for some show parallel extinction, indicating that at one time pyrrhotite occupied a large part of the field. A few inclusions are found in arsenopyrite, but almost none in marcasite or other minerals.

The pyrite network is a unique variation of the granular texture, and is composed of pyrite webs separated by angular cavities. Invariably some marcasite and arsenopyrite occur with the pyrite. The cavities are lined with subhedral to euhedral pyrite, but inclusions of pyrrhotite indicate that the pyrite is of replacement origin and not a true crustification (Fig. 30). Considerable pyrrhotite remains in a few specimens, and they show the network texture in an early stage of development (Figs. 24, 31). The pyrite webs first appear as broad veinlets in pyrrhotite, and the original fracture along the center of the veinlet is locally filled with later siderite and sphalerite II (Fig. 31). With a strong power of crystallization, the pyrite has formed perfect crystals in replacement, and the apparent druses represent the final wave



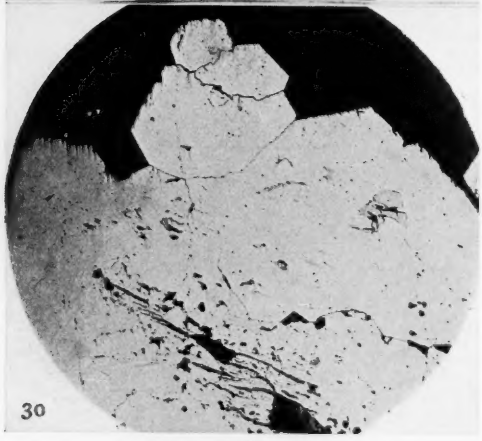


FIG. 29. Small grains of pyrite (white) in lamellar marcasite (light gray). Ragged borders suggest corrosion of pyrite by marcasite. Note euhedral pyrite parallel to marcasite lamellae. Forastera vein, 700 level. × 285.

FIG. 30. Euhedral replacement pyrite, with residual pyrrhotite, which parallels marcasite-siderite aggregate at lower margin. Animas vein, 1300 level. × 45.

in an advancing attack on pyrrhotite; an attack that progressed inward from fractures, from veinlets, and possibly from franckeite residuals, which are now represented by siderite areas of abnormal outline (Fig. 31). Late solution has removed the pyrrhotite walls, but the pyrite veinlets remain.

A common occurrence of pyrite, but not the most conspicuous, is that of tiny grains and crystals in the broad areas of lamellar marcasite. Some are perfect cubes and surrounded by siderite; others are highly irregular and appear to be corroded by marcasite (Figs. 25, 26, 29). Little, if any, pyrrhotite is found in the pyrite of this type, which may be earlier in age than the pyrrhotite.

The Marcasite-Arsenopyrite-Pyrite Sequence.—(Figs. 24, 31). The lamellar marcasite commonly forms a narrow band at early mineral contacts and it is followed outward by granular or massive pyrite. Between the two there may be a cellular zone made up of small aggregates and crystals of pyrite and arsenopyrite, forming a vague crust on marcasite. The larger pyrrhotite areas are cut by arsenopyrite veinlets, which terminate abruptly against the marcasite bands or merge with the cellular arsenopyrite-pyrite aggregate, evidence which indicates that the lamellar marcasite largely precedes the arsenopyrite. In the textures illustrated, the pyrite clearly follows the arsenopyrite, replacement working outward from the earlier arsenopyrite veinlets, which now mark the center of the pyrite webs. Concentric marcasite is of approximately the same age as the pyrite, and in places the two are hardly more than a textural variation in a simultaneous replacement (Fig. 28). Concentric marcasite deposition continued until sphalerite II appeared, the two minerals locally forming an intimate mixture of very fine grain.

Siderite and sphalerite II occur as coatings and interstitial fillings of late age, but both minerals precede the final elimination of pyrrhotite. Many of the larger vugs, from which the pyrrhotite has been removed, are not lined with either mineral; some cavities extend across siderite into pyrrhotite areas; and crusts of sphalerite II have become isolated by the continued solution of pyrrhotite (Fig. 24).

FIG. 31. Pyrrhotite (*Po*) replaced by complex veinlets of marcasite (*Mc*), arsenopyrite (*Aspy*), and pyrite (*Py*). Late filling of siderite (*Sd*), in places, perhaps replacing franckeite (*e.g.* point *x*). Reggis vein. × 42.

The sequence outlined in the foregoing paragraphs may be summarized as follows: (1) arsenopyrite-pyrite, (2) pyrrhotite, (3) lamellar marcasite, (4) arsenopyrite, (5) pyrite, (6) concentric marcasite, (7) siderite-sphalerite II, and (8) final solution of pyrrhotite.

The Franckeite Pseudomorphs.—Perfect pseudomorphs after franckeite are shown by pyrite and marcasite, and details of texture probably inherited from the same mineral are shown by wolframite, arsenopyrite, sphalerite, stannite, and siderite. Such textures were first interpreted as a direct replacement of franckeite, but certain facts suggest that pyrrhotite has been an intermediate product.

The many textural varieties of pyrite and marcasite exhibit numerous voids, distributed in various ways, and to a less degree the same is true of wolframite, arsenopyrite, stannite, and sphalerite; but the franckeite fibers in pyrrhotite, and the pyrrhotite grain boundaries are sharply defined. A loss in volume has taken place, and it seems to be more closely connected with the replacement of pyrrhotite than of franckeite. Applying this criterion, wolframite, sphalerite, stannite, marcasite, arsenopyrite, and pyrite, all of which are definitely later than franckeite, are also later than pyrrhotite.

The complex patterns of the late sulphides commonly exhibit a " regional parallelism " which extends throughout a large part of the specimen; a structure to which many details of texture conform: residuals of franckeite, franckeite cleavage, marcasite lamellae, step-like contacts between pyrite and marcasite, angular borders of arsenopyrite, stannite, and sphalerite, elongated pits, etc. (Figs. 25, 27, 28, 30, 32). This means that the minerals have been under a common control, but the parallelism seems to be more extensive than the pyrrhotite grain boundaries, and is probably related to franckeite, which developed in larger units. Nevertheless the complex pattern is made up predominantly of marcasite, arsenopyrite, and pyrite, minerals which are known to replace pyrrhotite on a wide scale; residuals of pyrrhotite in the pyrite conform to the regional parallelism; and the aggre-

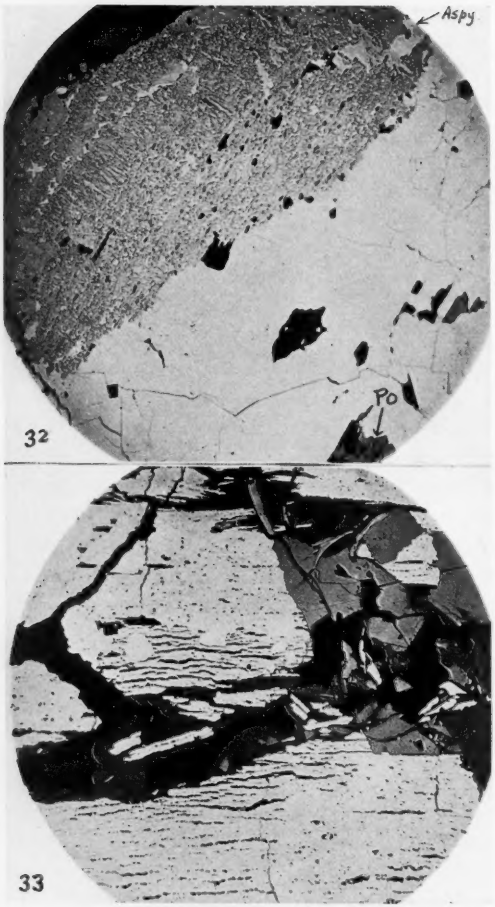


FIG. 32. Typical marcasite-pyrite texture. Lamellar marcasite favors early mineral contact (dark gray), and is parallel to pits and residuals of pyrrhotite (*Po*) in pyrite. Arsenopyrite patches (*Aspy*) of high relief in marcasite. Contacto vein, 1500 level. × 145.

FIG. 33. Principal field of marcasite and pyrite (nearly white). Stannite (light gray) and sphalerite I (dark gray) cut by veinlets and coated by sphalerite II (slightly darker than sphalerite I). Contacto vein, 1000 level. × 98.

gates are highly cellular, grading into the network texture, which can be definitely traced to the destruction of pyrrhotite. In short, the minerals have probably replaced pyrrhotite, but they have also acquired a "regional parallelism" which is probably inherited from the earlier franckeite.

The most delicate pseudomorphs of pyrite and marcasite after franckeite may likewise involve the replacement of pyrrhotite. The marcasite is identical with that which forms veinlets in pyrrhotite, the pyrite can be traced into near-by areas in which pyrrhotite inclusions are numerous, and the presence of irregular cavities, open contacts, and parallel pits suggests the same loss in volume that elsewhere is associated with the replacement of pyrrhotite. The evidence is just short of convincing that the platy and distorted structure of the franckeite has persisted through pyrrhotite into replacements of the second generation, forming in this way the perfect pseudomorphs, as well as the regional parallelism of the complex marcasite-arsenopyrite-pyrite aggregate.

Siderite.—Siderite occurs in the "pyritic" veins, particularly where sphalerite is abundant. As observed in polished section, it is a late mineral moulded about pyrite and arsenopyrite grains, filling in between the marcasite lamellae, and forming veinlets in marcasite (Figs. 25, 31). Less commonly it forms imperfect pseudomorphs after franckeite, and perhaps replaces residual fibers of franckeite in pyrrhotite (Fig. 31).

Sphalerite II was not observed in contact with siderite, but may be somewhat later. It occurs as a partial filling of the larger vugs of the network texture, whereas siderite is found with the marcasite-arsenopyrite-pyrite aggregates, which were probably developed at an earlier stage.

Late Sulphides and Gangue.—Sphalerite II, pyrite II, chalcopyrite, and a black soft gangue form crustifications and veinlets of late age. The principal sulphide is a very fine-grained sphalerite of concentric and globular form, slightly lighter in color than the early sphalerite. It has a dull white to light brown internal reflection, and a white color when immersed in melts of high

index. Ahlfeld [18] records wurtzite at Llallagua, but the material referred to here is isotropic, with an index of approximately 2.35. Sphalerite II generally forms a minute coating or tiny veinlets (Figs. 23, 33); but some occurrences suggest a replacement of stannite or of bismuthinite (Fig. 17). Small specks of chalcopyrite may be found with the sphalerite, especially in those tiny veinlets which cut stannite. Pyrite II fills fractures in pyrite I, marcasite, and earlier minerals. It is generally later than sphalerite II, but repeated deposition is also recorded.

The dark gangue is too fine-grained for identification, and probably includes more than one mineral. As a replacement of bismuthinite it may occur to the exclusion of sulphides, but commonly it forms a minute crust on sphalerite II (Fig. 23).

Wavellite.—Many open fissures are lined with large quartz crystals which are coated with botryoidal and finely crystalline wavellite. The latter also forms a crustification on cassiterite and sulphides, and in one specimen it occurs with globular masses of sphalerite II. The wavellite is obviously of late age, but its relation to sphalerite II is not clear.

Supergene Phosphates.—Several supergene phosphates are found at Llallagua, including vauxite, paravauxite, and metavauxite, first described by Gordon.[19] They are found as finely crystalline and silky coatings on wavellite and other minerals. Good specimens have been obtained at a depth of 1800 feet, but the principal occurrence is at a higher elevation. Vivianite also forms druses, and some of the crystals are large and remarkably transparent.

Minerals of the Oxide Zone.—The oxidized vein-filling presents a clay-like mass of light brown color, a cellular aggregate of iron oxides, or a mixture of quartz, "limonite," and cassiterite. The universal ore mineral of the oxide zone is cassiterite of residual origin, as already described. Small quantities of antimony, bismuth, zinc, lead, etc. probably exist in the oxide zone, but definite mineral species were not identified. Ahlfeld [20] men-

[18] *Op. cit.*, p. 253.

[19] Gordon, S. H.: Proc. Phila. Acad. Nat. Sci., vol. 75, pp. 261–270, 1923.

[20] *Op. cit.*, page 251.

tions bismuth ocher and karelinite. Most of the iron oxide may be classed as "limonite," but in some thin sections jarosite forms a crust on cassiterite. It is yellow to reddish brown in color and composed of small plates and radiating groups (Fig. 16).

Other Minerals.—The characteristic minerals of Llallagua have been described, but several others occur as rare vein constituents. Chief among these is apatite, which forms tabular and prismatic crystals associated with quartz and cassiterite. Native bismuth was not observed in the mine but occurs in one polished specimen with bismuthinite, the latter forming residual rims along contacts with euhedral quartz, and scattered residuals in the native bismuth.

Muscovite, monazite, tetradymite, and galena were also identified. The muscovite is of about the same age as the quartz (Fig. 14), and the tetradymite is closely associated with bismuthinite (Fig. 17). Supergene minerals of minor importance include chalcocite and covellite, and probably chalcedony. Other minerals have been reported from Llallagua, but to list them would add little of significance.

Hypogene and Supergene Deposition.—The principal vein filling is unquestionably hypogene, but toward the surface the veins have been profoundly affected by supergene oxidation, and the break between hypogene and supergene deposition is, therefore, of major importance. The early vein minerals, quartz, cassiterite, and pyrrhotite, are unquestionably hypogene, and the same applies to franckeite, since it is the only important antimony mineral of the deposit.

The supergene alteration of pyrrhotite to marcasite is well known,[21] but the lamellar marcasite of Llallagua is hypogene. It largely precedes the principal deposition of arsenopyrite and pyrite; it is followed by siderite, sphalerite II, pyrite II, and chalcopyrite, a group which is more likely hypogene than supergene; and it is found with arsenopyrite 2400 feet from the surface, and fully 400 feet below the ground-water level.

[21] Lindgren, Waldemar: Mineral Deposits, 3rd. Ed., p. 937. New York, 1928. Newhouse, W. H.: ECON. GEOL., vol. 22, pp. 54–64, 1927.

The fine-grained iron sulphide of concentric structure is somewhat similar to the concentric marcasite which has been described as a supergene alteration of pyrrhotite in other localities. At Llallagua it is later than the lamellar type, and possibly it is supergene; but if so, the principal deposition of pyrite is also supergene, a conclusion contrary to the repeated observation that supergene pyrite is rare, even in ore deposits with pronounced sulphide enrichment.

Siderite, sphalerite II, pyrite II, and chalcopyrite largely follow the concentric marcasite but, to judge from their associations elsewhere, the minerals are probably hypogene.

The occurrence of wavellite as a late crustification admits of a supergene origin, and it is listed as a supergene mineral by Lindgren [22] but included with the hypogene phosphates by de Launay.[23] Ahlfeld [24] attributes the Llallagua wavellite to the supergene alteration of apatite, but there is hardly enough apatite in the ore to account for the phosphorus, and there is no evidence to show that apatite was ever more abundant.

In summary, supergene alteration may possibly begin with sphalerite II and pyrite II, but it can hardly include much of the concentric marcasite which is so closely associated with pyrite, a typical hypogene mineral of almost universal distribution. The removal of pyrrhotite to form the network texture was, locally at least, a late event following the deposition of sphalerite II, and it may have been caused by acid waters of surface origin. The distribution of the texture in the field is not known with sufficient accuracy to decide the point.

(*To be concluded in next number.*)

[22] *Op. cit.*, page 318.

[23] De Launay, L.: Gites Mineraux et Metalliferes, vol. 1, page 643, 1913.

[24] *Op. cit.*, p. 253. Kozlowski records primary wavellite at Oruro. (Archiwum Mineralogiczne, Warsaw, vol. 8, p. 54, 1932).

OCCURRENCE OF ENARGITE AND WULFENITE IN ORE DEPOSITS OF NORTHERN ARKANSAS.[1]

EDWIN T. McKNIGHT.

INTRODUCTION.

ONE of the several contrasting features between zinc and lead deposits of the Mississippi Valley type and those of the Cordilleran type is the mineralogic simplicity of the Mississippi Valley ores. Because the usual ore and gangue minerals are few in kind and are those that can conceivably be carried in solution by circulating ground waters, special theories of origin that have prevailed for the Mississippi Valley deposits have carried more weight than might be the case if the ores were chemically and mineralogically more complex. In summarizing the characters of the Mississippi Valley type, Lindgren[2] points out that the elements gold, antimony, arsenic and molybdenum are almost wholly absent. In view of this long recognized dearth of certain elements, it is believed that the discovery of two of them in typical Mississippi Valley lead and zinc ores of northern Arkansas may be of some interest.

OCCURRENCE.

Northern Arkansas contains widely scattered deposits of zinc and lead in the Paleozoic limestones and dolomites north of the Boston Mountains. Traces of metallic minerals have been found in practically all the counties from the Oklahoma line on the west to the Coastal Plain on the east, but commercial production has been confined to two broadly defined areas, of which the western and more productive one comprises Marion, Searcy, Newton, and Boone counties and part of Baxter county, and the eastern one

[1] Published by permission of the Director of the U. S. Geological Survey.

[2] Lindgren, Waldemar: Mineral Deposits, 4th ed., p. 423, 1933.

comprises Sharp and Lawrence counties. Structurally, the ore deposits of both areas resemble the better-known deposits of the Tri-State region in that they occur chiefly in runs and blankets, more rarely along faults. The runs and blankets are found in horizontal or nearly horizontal rocks and are limited to certain beds in which the mineralization has followed zones of shattering, produced by very slight structural deformation. The runs, which are commonly of a linear shape, are simply the more richly mineralized portions of the blankets, formed along the main channels of circulating ore solutions. Although runs may occur in the rocks outside of faulted districts and may prove to be richly mineralized, the minor adjustments to stresses that are set up in the neighborhood of major faults have in many places been of the requisite type and amount to produce ore runs most abundantly. The faults themselves, however, with a few notable exceptions, are barren.

Mineralogy.—The primary ore minerals of the northern Arkansas deposits are sphalerite and galena. The sphalerite is widely distributed over the region, but the galena is restricted to certain districts, being conspicuously absent from those districts in southern Marion county and northern Searcy county, which have produced most of the zinc. Small amounts of chalcopyrite are widely distributed but this mineral is nowhere present in commercial quantity. The amount of pyrite is nowhere great enough to affect the commercial grade of the ore, and marcasite has been identified at only one prospect. The gangue minerals are jasperoid (which replaces the country rock), pink-spar dolomite, quartz, and calcite. Aside from variations in lead content, the mineralizing solutions appear to have been very similar throughout the region, and the differences that appear in the ore deposits result chiefly from differences in the character and texture of the country rock.

Enargite.—At the Governor Eagle mine, 10 miles northwest of Yellville, Marion county, enargite is associated with the more usual sphalerite, a little chalcopyrite, and minor amounts of dolomite (pink spar), calcite, and quartz gangue. The mine work-

ings consist of three shafts reported to be from 85 to 110 feet in depth, but they are filled with water and are at present inaccessible. A small amount of sulphide and silicate (calamine) ore, taken out at the last working in 1917, has been left in the ore bin. Specimens from this bin were collected in 1928 by the writer, but so inconspicuous is the enargite that it was not found until these specimens were examined more carefully in the laboratory some time later. Subsequently, a specimen collected by E. F. Burchard at the time that the mine was being worked, in 1916, was found to show especially good crystals.

The ore body is contained in the Everton formation, which is of Lower Ordovician age. The ore run at the bottom of the shafts is reported to be 20 feet thick and to pitch rather steeply to the east, in contrast to the more nearly horizontal attitude of most other ore bodies in the northern Arkansas field. About 3 per cent. of the material along the run is sphalerite; the rest consists chiefly of shattered fine- to coarse-grained gray dolomite, which makes up the country rock, although a small percentage of gangue material is present. The sphalerite is rosin-colored and tends to crystallize rather coarsely in open vugs, similar to its mode of occurrence in the Tri-State district. Small crystals of chalcopyrite are rather thickly peppered on the free surfaces of the sphalerite crystals, and, sporadically, individual small crystals or nests of small crystals of enargite occur also on the sphalerite. The final mineral to crystallize was calcite, in modified flat negative rhombohedrons, which lie on top of the sphalerite and enclose the underlying copper-bearing minerals. Dolomite, in pinkish curved crystals, is in part later than the sphalerite, but some of it may be contemporaneous with or even earlier than the sphalerite. The quartz, of which only a small amount is present, is early in the paragenetic sequence.

The enargite crystals have been examined by W. T. Schaller, who states that they are "of typical enargite habit, flattened parallel to $a(100)$, with medium-sized faces of $m(110)$, line faces of $b(010)$, and large dull faces of $c(001)$ (see Fig. 1, A). On one crystal a small face of $s(011)$, dull and giving no reflec-

tion, was observed" (see Fig. 1, B). The crystals average 1 millimeter in size but attain a maximum, in the specimens examined, of 4 millimeters.

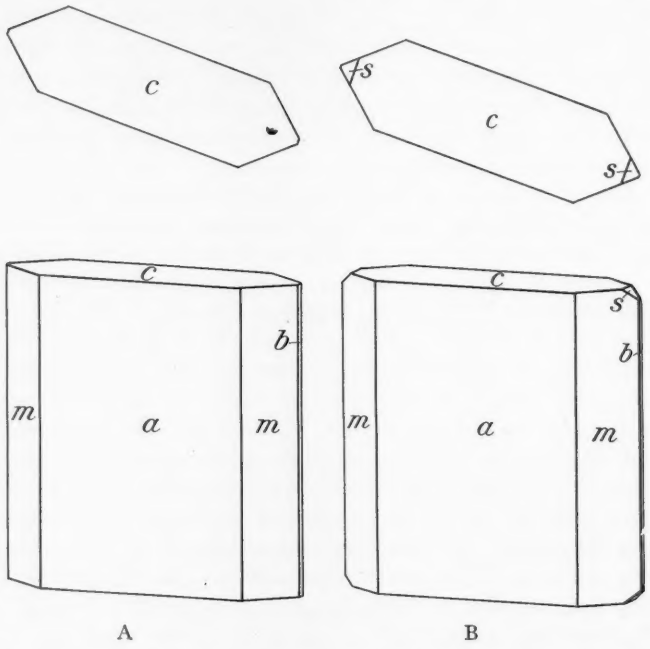


FIG. 1.—Crystal forms of enargite from Governor Eagle mine, Marion County, Ark. In A, the face $b(010)$ is drawn wider than it actually is.

Wulfenite.—Wulfenite occurs with cerussite as an oxidation product of galena at the Shiras mine, which lies 6 miles north of Cotter and 1 mile southeast of Amos, Baxter county. The mine opening is a drift going 120 feet into the hill in deeply weathered Cotter dolomite (Lower Ordovician). The primary galena was apparently scattered through the dolomite as isolated masses, commonly weighing several pounds each, without definite devel-

opment of a run. Upon weathering, the galena is retained in the residual clay. Attached to the surfaces of the galena masses are clear crystals of wulfenite and cerussite. Those of wulfenite attain a quarter of an inch in diameter and are rather poorly formed but otherwise typical. Polished sections of the galena were examined for molybdenite, which is commonly assumed to be the primary source of the molybdenum in oxidized lead deposits, but none was found. The only primary gangue mineral recognized in the oxidized material is drusy quartz, which may be attached to the galena. The galena carries 0.09 ounce of silver to the ton.

CONCLUSIONS.

These occurrences of arsenic and molybdenum minerals in northern Arkansas are believed to be the only ones thus far recognized in the typical zinc-lead ores of the Mississippi Valley.[3] Waring [4] reports arsenic and antimony in the zinc ores of southern Wisconsin, but no minerals are cited, and the presence of these elements appears to be revealed only as a result of analysis of sulphuric acid from pyrite roasting.[5] Fowler and Lyden [6] report 0.009 per cent. of arsenic in an average sample of Joplin-Miami zinc concentrates, although the form in which it occurs has not been ascertained.[3] Arsenic is a chemical constituent of the pyrite in ore deposits of the Mississippi Valley type in Silesia,[7] and at the Bleischarley mine, in the same district, jordanite ($4PbS.As_2S_3$) is reported to occur. On the whole, however, the occurrence of arsenic, antimony, and molybdenum, other than in deposits of recognized magmatic origin, is rare.

[3] Since this article was written, enargite with crystal habit and mode of occurrence similar to that of the enargite here described from the Governor Eagle mine has been found by the writer in the Barr and Bendelari mines near Treece, Kansas.

[4] Waring, W. G.: The Zinc Ores of the Joplin District. Amer. Inst. Min. Eng. Trans., vol. 57, p. 664, 1918.

[5] Chas. H. Behre, Jr., (personal communication) confirms this occurrence for arsenic.

[6] Fowler, G. M., and Lyden, J. P.: The Ore Deposits of the Tri-State District. Amer. Inst. Min. Met. Eng. Trans., vol. 102, p. 234, 1932.

[7] Lindgren, Waldemar: Mineral Deposits, 4th ed., p. 427, 1933.

ACKNOWLEDGMENTS.

The writer is indebted to M. N. Short, of the University of Arizona, formerly of the United States Geological Survey, for the microchemical and optical identification of the enargite; to W. T. Schaller, of the United States Geological Survey, for notes on the crystal habit and for the drawings (Fig. 1) of enargite; and to Charles Milton, of the United States Geological Survey, for corroborative identification of the wulfenite.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.

AN OCCURRENCE OF SCHWATZITE IN BRITISH COLUMBIA.

HARRY V. WARREN AND CLIFFORD S. LORD.

SCHWATZITE, or mercurial tetrahedrite, has not previously been recorded from British Columbia and, since it is of rare occurrence throughout the world, it is hoped that this brief description may prove of interest.

History.—In investigating the varieties of tetrahedrite found in British Columbia, one of the samples was found to contain mercury. The sample came from the Pretty Girl claim of the North Kootenay Mines, Ltd., situated about 18 miles west of Windermere on the summit of the divide between the headwaters of Boulder and Law's Creek, at an elevation of 9,250 feet, on the east slope of the Purcell Range. Some work has been done on the claim but it is not now being worked.

Through the courtesy of the British Columbia Chamber of Mines, several pounds of ore from the North Kootenay Mine was obtained for examination.

Occurrence.—The property is described in the British Columbia Minister of Mines Reports.[1] From these reports has been taken the following description of the deposit.

A mineralized zone, some 6–8 feet wide, occurs in steeply dipping soft shales trending N. 25° W. Gray copper ore, with accompanying carbonates, lies between the layers of the shales or slates.

The rocks in this area are of Late Pre-Cambrian age and not far distant there are batholithic intrusions which are believed to be of Jurassic age.[2]

"There seems to be no vein in the usual acceptance of the term, but a zone in the bedding of the shales. . . ." A repre-

[1] B. C. Minister of Mines, Annual Report, 1898, pp. 1042–1054.

[2] Walker, J. F.: Canadian Geol. Survey, Mem. 148.

sentative sample is stated to contain 26.68 per cent. of copper and 55.5 ounces of silver per ton. Evidently the sample was carefully selected.[3]

In the 1915 report, mention is made of a vein "which varies from a seam up to 10 inches in width, consisting of quartz somewhat stained with malachite."[4]

Assays of grab samples gave 20.8 per cent. of copper and 38 ounces of silver per ton. The presence of mercury apparently was never suspected. From the meager information at hand it is impossible to express an opinion as to the value of the deposit.

Other Deposits of the Windermere District.—The deposits of this district are of the lead-silver-zinc or mesothermal type as defined by Lindgren.[5]

In this district tetrahedrite occurs in many of the mines, and through the courtesy of Dr. J. F. Walker a number of other samples of tetrahedrite were examined. None contained any mercury.

The Ore.—The specimens show little variation and all may well have come from one large lump of ore. The sample, therefore, may not be representative of the deposit.

The ore appears to occur in two bands, a band of massive and comparatively pure tetrahedrite against a band of sparser mineralization in a finely crystalline gangue composed largely of barite. Chalcopyrite with pyrite can also be seen in small quantities, together with some products of oxidation, of which limonite, malachite, and azurite are conspicuous.

Microscopic Description.—The following minerals have been recognized: tetrahedrite (mercurial), pyrite, chalcopyrite, bornite, chalcocite, azurite, malachite, barite, and quartz. In the massive ore, tetrahedrite, pyrite, and chalcopyrite occur in a gangue of quartz. In the disseminated mineralization the minerals are too fine-grained and too intimately intergrown to permit of satisfactory determination. The following remarks concerning the paragenesis of the ore refer, therefore, to the massive ore. The

[3] Authors' comment.

[4] B. C. Minister of Mines, Ann. Rept. 1915, p. 96.

[5] Lindgren, W.: Mineral Deposits, 1928, p. 599.

more important minerals were deposited in the following order: quartz, pyrite, chalcopyrite, tetrahedrite, barite. Overlapping and contemporaneous deposition occurs in the case of chalcopyrite and tetrahedrite.

Selection for Analysis.—Tetrahedrite is reasonably free from impurities in some parts of the deposit. Some of the "cleanest" material was broken off, crushed and screened, and as clean material as possible picked out for analysis. A representative sample of this selected material was then embedded in a damar section, polished and examined under the reflecting microscope. This material, although reasonably pure, contained a little chalcopyrite in irregular spots and a few patches of a dark black-earth mineral which could not be determined, and also a little barite.

Analysis.—The selected material was again picked over, under binoculars, and this product was then assayed with the following results:—

	%		%
Copper	33.8	Iron	1.0
Silver	.2	Antimony	23.4
Lead	——	Arsenic	1.4
Zinc	4.0	Sulphur	22.1
Insol.	4.9	Mercury	6.1
		Total	96.9

Taking out the insoluble and correcting to 100 per cent., gives:

Copper	36.8	Antimony	25.4
Silver	.2	Arsenic	1.5
Zinc	4.3	Sulphur	24.0
Iron	1.2	Mercury	6.6
			100.0

It was not practical to obtain enough pure material for a complete check but, as great pains were taken to ensure the accuracy of the analysis and particularly to allow for the effect of the mercury on the copper determination, it is reasonably safe to assure that this analysis is accurate.

The low total may be satisfactorily explained as follows:—

(1) The presence of copper carbonates in minute amounts.

(2) Barite gangue entering into the material. Analyses neither of Ba nor of SO_4 were attempted.

(3) The possible presence of other elements not recognized in this somewhat unusual ore.

Dividing by atomic weights gives the following atomic proportions:

Copper	.575	Antimony	.211
Silver	.002	Arsenic	.020
Zinc	.066	Sulphur	.750
Iron	.021	Mercury	.030

Iron was deducted as chalcopyrite impurity. Elements of corresponding valence were grouped, giving:

Copper, Silver	.56	Antimony, Arsenic	.23
Zinc, Mercury	.10	Sulphur	.71

It will be seen that these atomic proportions will produce no simple formula although they correspond reasonably with the formula, $3(CuAg)_2S$, $(HgZn)S$, $(AsSb)_2S_3$.

Physical Properties.—Crystallography—No evidence; Specific Gravity—4.83; Color—Silvery white to gray; Color of Powder—Dark reddish brown; Luster—Metallic; Hardness—About 4; Cohesion—Less brittle than normal tetrahedrite; Fracture—Uneven. Conchoidal in detail; Cleavage—None.

Microchemical Tests.—Similar to those of normal tetrahedrite. Some specimens seem to show a more decided reaction with HNO_3 than do the ordinary varieties. It may best be distinguished by blowpiping, a globule of mercury being easily obtained on charcoal.

Origin.—It is impossible to do more than speculate as to the origin of the occurrence, but it seems reasonable to assume that it belongs to a type of deposit intermediate to the Epithermal and Mesothermal of Lindgren.[6] Possibly it may fit in with Graton's newly proposed leptothermal zone.[7]

[6] Lindgren, W.: *Op. cit.*

[7] Graton, L. C.: ECON. GEOL., vol. 28, p. 537, 1933.

Acknowledgments.—All the work was done in the Geological and Metallurgical Laboratories of the University of British Columbia. The authors wish to express their thanks to the many persons who co-operated, in particular to Mr. J. D. Galloway, the Provincial Mineralogist, and Mr. F. Woodside, Manager of the British Columbia Chamber of Mines, for their help in obtaining specimens. We are also greatly indebted to Professor H. N. Thomson for guidance in the analytical work; to Mr. W. B. Bishop, who kindly supervised the fire assaying; and to Dean R. W. Brock and Dr. S. J. Schofield, who offered valuable advice and criticism.

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EVALUATION OF ASH CORRECTION FORMULÆ BASED ON PETROGRAPHIC ANALYSES OF MINERAL MATTER IN COAL.[1]

C. G. BALL AND G. H. CADY.

INTRODUCTION.

PETROGRAPHIC investigation of the identity, character, distribution, and abundance of mineral constituents in Illinois coals has been undertaken by the Illinois State Geological Survey because of lack of information on mineral matter in coal, and because of the necessity of such information to stratigraphic, physical, microbotanical, and benefication investigations now in progress.

Only the first stage of the investigation has been completed, consisting of a detailed determination of the minerals separable by float and sink methods from a complete column of coal No. 6, obtained in the New Orient Mine of the Chicago, Wilmington, and Franklin Coal Co., located at West Frankfort, Illinois. The results obtained are, however, sufficiently conclusive to justify certain generalizations in regard to the validity of ash correction formulae in common use for deriving mineral matter-free values, such values being the approved basis of scientific classification of coal by rank.

GENERAL METHODS AND RESULTS OF INVESTIGATION.

The original column, representing a thickness of 89.1 inches, did not include 10.1 inches of top coal and 7.7 inches of bottom coal. From the original column 75 small blocks were cut and examined individually, each block representing one-half to six inches of the bed. After the mineral matter in the collected column was studied, previously unrepresented portions of the top and bottom

[1] Published with the permission of the Chief, Illinois State Geological Survey, Urbana, Illinois. Presented before the Society of Economic Geologists, Chicago Meeting, December, 1933.

of the bed were collected and the mineral matter separated and examined. Chemical determinations of the quantity of ash and the composition of the ash residue after removal of the separable mineral matter were made for five benches representing the full thickness of the bed. The results of the study provided detailed

TABLE I.

SEPARABLE MINERAL MATTER IN COAL NO. 6 WITH THEORETICAL DERIVATIVES.

A. Minerals.

Bench	Thick. in Inches	No. of Blocks[a]	Total Mineral Matter %	Kaolinite		Pyrite		Calcite	
				In Coal %	In MM %	In Coal %	In MM %	In Coal %	In MM %
V[b]	10.1	3	3.15	0.71	22.49	1.81	57.44	0.63	20.07
IV	30.7	20	1.49	1.33	89.53	0.09	6.01	0.07	4.46
III	44.5	45	2.51	2.02	80.56	0.32	12.72	0.17	6.72
BB[c]	1.6	—	—	—	—	—	—	—	—
II	12.3	10	7.30	2.97	40.73	0.10	1.35	4.23	57.91
I[d]	7.7	2	4.27	1.49	34.97	0.02	0.50	2.76	65.54
II–IV[e]	89.1	75	2.79	1.90	68.27	0.21	7.44	0.68	24.29
I–V[f]	106.9	80	2.98	1.67	56.05	0.45	15.07	0.86	28.87

B. Theoretical Derivatives.

Bench	Al_2O_3		SiO_2		Fe_2O_3		CaO		Hyd. H_2O %	CO_2 %	Sp %	Ash %
	In Coal %	In Ash %	In Coal %	In Ash %	In Coal %	In Ash %	In Coal %	In Ash %				
V	0.28	12.96	0.33	15.28	1.20	55.56	0.35	16.20	0.10	0.28	0.97	2.16
IV	0.52	41.93	0.62	50.00	0.06	4.84	0.04	3.23	0.18	0.03	0.05	1.24
III	0.80	39.22	0.94	46.08	0.21	10.29	0.09	4.41	0.28	0.07	0.17	2.04
BB	—	—	—	—	—	—	—	—	—	—	—	—
II	1.17	23.45	1.38	27.65	0.07	1.40	2.37	47.50	0.41	1.86	0.05	4.99
I	0.59	20.77	0.69	24.30	0.01	0.35	1.55	54.58	0.21	1.21	0.01	2.84
II–IV	0.75	34.88	0.88	40.93	0.14	6.51	0.38	17.67	0.26	0.30	0.11	2.15
I–V	0.66	29.73	0.78	35.13	0.30	13.51	0.48	21.62	0.23	0.38	0.24	2.22

[a] Individual blocks from 1/2–6" in thickness.
[b] Top coal, not mined.
[c] Blue band, not included in sample.
[d] Bottom coal, not mined.
[e] Average representing thickness of mined coal.
[f] Average representing total thickness of bed.

knowledge of the identity and amount of the separable mineral matter in the coal, the amount of ash not separable by the float and sink method employed, and the chemical nature of this residue.

Concentration of mineral constituents for petrographic analysis was effected by separating the "float" and "sink" fractions of finely ground coal in separatory funnels, using a liquid of 1.70 specific gravity as the separating medium. By examination of the "sink" portions of samples from successive levels in the coal bed, vertical variation in abundance and composition of separable mineral matter was established, the resulting data being assembled by dividing the entire column into five benches as designated in Table I. The three middle benches represent the coal customarily mined in Franklin County, while the upper and lower benches are usually left in the mine.

Character and Composition of Separable Mineral Matter.—Separable mineral matter in coal consists of (1) primary impurities which were washed, blown, or otherwise transported into the peat swamp, and (2) secondary impurities which were precipitated directly from infiltrating solutions or concentrated by circulating waters either during or after coalification.

The primary impurities in the coal seam consist mainly of detrital clay, which occurs as horizontal partings or bands in the coal, or is disseminated through its attrital layers. The amount of this clastic material found in the New Orient coal, excluding the blue band, a characteristic wide-spread clay parting, does not exceed 19 per cent. of the mineral matter. Other detrital particles are also present in nearly every coal level, consisting of minerals normally present in sandstones accompanying the coals. A list of the detrital minerals, with the exception of the clay, is given in Table II, which also indicates the distribution of each mineral by benches. The non-clay detrital minerals, though persistent, are quantitatively of little importance, composing less than one per cent. of the total separable mineral matter, or less than one-tenth of one per cent. of the coal.

More than ninety-nine per cent. of the recovered mineral

TABLE II.

DETRITAL MINERALS IN COAL NO. 6.

Bench No.	I	II	III	IV	V
Apatite		x	x	x	
Biotite		x	x	x	
Chlorite			x		
Epidote				x	
Feldspar[a]	x	x	x	x	
Garnet		x	x	x	
Hornblende		x	x	x	
Kyanite		x	x		
Muscovite			x	x	
Rutile			x	x	
Quartz	x	x	x	x	x
Staurolite			x		
Topaz				x	
Tourmaline			x	x	
Zircon		x	x		
Opaque minerals[b]					

[a] Both orthoclase and plagioclase varieties.
[b] Opaque minerals observed but not specifically identified.

matter consists of the precipitated minerals, calcite, pyrite, and kaolinite, and the primary detrital clay. The precise mineral identity of the clay has not been established but it appears to have about the composition of kaolinite. The abundance of each of the three mineral constituents, regarding clay as kaolinite, and their relations to the total separable mineral-matter content, are given in Table I for each bench of coal No. 6, for the commonly mined thickness, and for the total thickness of the bed.

No method for the quantitative separation of the detrital clay from the kaolinite has been perfected in the present investigation. Visual examination and microscopic counts of the clay constituents, however, indicate that the detrital clay is important only in the clay partings, and that it does not compose more than twenty-five per cent. of the total clay and kaolinite portion of the mineral matter. Clay partings are largely fortuitous in character and in general separate certain benches of the coal seam.

Mineral Matter not Recovered by Float and Sink Methods.—The amount of mineral matter remaining in the coal after separa-

tion of the recoverable minerals as determined by ashing varied in the five samples ashed from 2.6 to 9.5 per cent. (Table III). The extent to which this unrecoverable mineral matter may be organically combined is of importance in this study. Since only about one-third of the total ash in the coal is represented by the recovered mineral matter (Table III, col. 4) it is probable that not all of the inorganic mineral matter is recoverable by the methods used. Furthermore, it is improbable that other varieties of minerals than those recovered are present in the fine material that passed through the separating process. This conclusion is verified by the results of chemical analysis of the ash as described in the following paragraph.

TABLE III.

RELATIVE IMPORTANCE OF ASH-FORMING CONSTITUENTS OF KAOLINITE, PYRITE, AND CALCITE IN COAL FROM WHICH SEPARABLE MINERALS WERE REMOVED.

	1	2	3	4	5	6	7	8	9	10	11
Block No.	Calcul.[a] Ash %	Determined Ash %	Total Ash %	Removable Ash % in Ash	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	CaO %	Total %	SO_3 in Ash	$\frac{\text{Col. 9}}{1.00-SO_3}$
V....	2.16	4.9	7.06	30.6	31.08	16.31	47.66	2.75	97.80	.59	98.38
IV...	1.24	2.6	3.84	32.3	50.75	28.19	13.80	2.74	95.48	1.09	96.53
III...	2.04	7.6	9.64	21.2	59.40	25.85	8.12	1.21	94.58	.10	94.67
II....	4.99	8.2	13.19	37.8	38.36	14.30	7.93	23.15	83.74	11.29	94.40
I.....	2.84	9.5	12.34	23.0	52.33	13.53	5.21	19.72	90.79	5.57	96.14

[a] Calculated from determined mineral matter (Table I).

Analyses were made of the ash derived from samples of coal representing the full section of each bench after the removal of separable mineral matter (Table III). When the values shown in these analyses are recalculated in terms of kaolinite, calcite, pyrite, and silica, it is found that 94 per cent. or more of the material in the ash is accounted for. Silica is present, at times in considerable excess, above that necessary to combine with the alumina to form kaolinite, and is much the largest component not readily associated with any other constituent present in the ash.

At the present time it is impossible to say how this silica occurs in coal, but the two most reasonable possibilities are that it is either finely divided quartz of detrital origin or silica of organic origin although not necessarily in organic combination. This is a problem inviting further investigation. Other substances such as titanium, sodium probably linked with chlorine, magnesium probably as a carbonate, and potassium, are present in amounts representing in each case not more than 2 per cent. of the ash. It appears, therefore, that the total ash consists mainly of three minerals found by float and sink methods and additional silica of highly variable amount, with organically combined mineral matter not exceeding 4½ per cent. of the ash.

A disturbing factor in ash evaluation in terms of mineral matter is the tendency of any calcite which may be present to combine rather tenaciously with sulphur released in the oxidation of the pyrite during combustion of the coal, particularly when ashing in large quantities, forming calcium sulphate.[2] The entire amount of calcium oxide present in the ash may be so combined with all the sulphur available from the pyrite. This increases the total quantity of the ash beyond the amount that would be present if the components were present simply in the form of oxides, and is of particular importance in high sulphur and high calcite coals. In order to put ash values given in Table III on a basis similar to those in Table I, the SO_3 is eliminated from the ash, the resulting total proportions of the ash, consisting of alumina, silica, calcium oxide, and ferric oxide, being given in column 11 of Table III.

USE OF MINERAL MATTER DETERMINATIONS IN CHECKING ASH CORRECTION FORMULÆ.

Detailed knowledge of the actual mineral constituents in coal is of particular value in determining the cause of variations in the behavior of the ash during combustion of the coal and in the evaluation of formulæ designed to convert coal ash values into

[2] Von Iw. Trifonow. Das Problem der Schwefelverteilung bei der Verbrennung von Kohle und Koks. Brennstoff-Chemie, vol. 13, (17), pp. 328–329, Sept. 1, 1932.

mineral matter values for classification purposes. We are particularly interested at this time in the latter application.

It has long been recognized that comparison of coals is most satisfactory when using mineral-free values calculated to either the moist or the dry basis. The computation of such values depends upon the preliminary determination of the theoretical mineral-matter values. The formula which has met with the greatest approval in the derivation of mineral matter values from the items of the proximate analyses is expressed in the ash correction portion of the Parr unit coal formula:[3]

$$\text{Mineral matter} = 1.08 \times \text{Ash} + .55 \times \text{Sulphur}.$$

In this and following formulae, ash, sulphur, and other values are given as fractions of unity.

The Parr formula is based upon the assumptions (1) that all mineral matter is composed of clay and pyrite, (2) that all of the sulphur is pyritic, and (3) that water of hydration in the clay is 8 per cent. None of these assumptions is correct, and the calculated value for mineral matter may be considered erroneous unless the errors compensate one another or are so small as to be unimportant. Confidence in the approximate accuracy of the Parr ash-correction formula rests upon uniformity of unit coal values derived by its use, particularly the unit calorific values, over a considerable area such as a county. Assuming the validity of the premise that such uniformity of the pure coal exists, any formula which will give uniform values should be regarded with favor. We have no reason to question the validity of the premise and, for the purposes of this presentation, will therefore assume that it is correct.

Even though the results obtained by the use of the Parr formula are prevailingly satisfactory, the fact that irregularities in unit coal values are found, and that the formula itself is obviously theoretically inaccurate, and the further possibility that regional variations in unit coal values may be inaccurately indicated due to regional variation in the character and amount of

[3] Parr, S. W. The Classification of Coal. Univ. Illinois Eng. Expt. Sta. Bull. 180, 1928.

the ash, makes critical examination of the formula advisable from time to time, as knowledge of the actual mineral composition of the coals improves. In the following paragraphs, therefore, critical consideration will be given to the ash correction portion of the Parr formula as given above and to a form of the Parr formula slightly modified by Thiessen [4] which provides a somewhat different correction for the presence of calcite in the coal than that originally proposed by Parr. This modified ash-correction formula is stated as follows:

$$\text{Mineral matter} = 1.08 \times \text{Ash} + .9 \times CO_2 + .55 \times \text{Sulphur}.$$

Evaluation of the Parr Formula.

Assuming that the mineral matter is composed entirely of kaolinite, calcite, and pyrite (or marcasite), ashing will produce a theoretical residue composed of alumina, silica, calcium oxide, and ferric oxide, to each of which definite values can be assigned and whose sum equals the total amount of theoretical ash. If the Parr ash-correction formula is then applied to this theoretical ash value, the resulting calculated mineral-matter value should coincide with the actual total mineral-matter value, provided that the formula is correct. In view of the obvious lack of definite relationship between terms of the Parr formula and the mineral constituents present, it is inconceivable that there will be perfect agreement, although agreement may be relatively close because of compensating errors in the formula, and the formula may be accepted as generally applicable. At any rate the possibility of considerable deviations arising from the use of the formula requires examination.

Mineral Matter to Ash Ratio.—It is evident that the critical consideration in evaluating the formula is the ratio of mineral matter to ash. This should closely agree with the ratio between determined mineral value and the theoretical ash derived therefrom. A definite theoretical ratio exists if the mineral matter

[4] Thiessen, G., and Reed, F. H. Studies of the Graphical Method for Calculating Pure Coal Calorific Value. Paper presented before the Gas and Fuel Division, A. C. S., Sept., 1933. Illinois Geol. Survey, Rept. of Invest. 32, pp. 57–99, 1934.

consists entirely of one constituent. For kaolinite this ratio is 1.16; for pyrite 1.51; and for calcite 1.79. The greatest possible theoretical variation in the ratio is therefore from 1.16 to 1.79.

The mineral matter to ash ratio as determined by the Parr formula may be expressed as follows:

$$\frac{\text{Mineral matter}}{\text{Ash}} = 1.08 + .55 \times (\text{sulphur/ash}).$$

It is apparent from this manner of expression of the relationships that the mineral-matter to ash ratio can never be less than 1.08 and that the amount by which it exceeds 1.08 will be determined entirely by the ratio of sulphur to ash. This ratio in Illinois coals varies for county average values from .10 to .64, the average ratio being .36. In certain individual instances the amount of the sulphur and ash are equal and the sulphur ratio is 1.00. With such a high ratio of sulphur to ash, the mineral-matter to ash ratio becomes 1.63 ($1.08 + .55 \times 1.00$). The probable range of variation, however, is between about 1.13 and 1.43 (for S/A ratios of .10 and .64 respectively), as compared with a theoretical range of 1.16 to 1.79. However, this wide theoretical range should be cut down to about 1.16 to 1.56, because calcite is rarely present in an amount of more than 1/5 of the ash. It appears, therefore, that the ash-correction formula applied to Illinois coals will give a range in the mineral-matter to ash ratios closely comparable with that theoretically obtained from various proportions of calcite, pyrite, and kaolinite in the amounts in which these are present in Illinois coals.

THEORETICAL ERRORS IN THE PARR FORMULA.

In view of the general agreement in the range of variation of the mineral-matter to ash ratios as described above, it is of importance to know whether the variations in the ratios obtained by the Parr formula will be of the same nature as the theoretical variations. Possibility of disagreement arises theoretically from three causes: (1) The moisture correction factor (.08) is not the same as the moisture correction factor for the ash of kaolin;

(2) the reported sulphur is not all pyritic and the relative amount of pyritic sulphur varies considerably; and (3) no allowance is made for the presence and variations in amount of calcite.

(1) *The Moisture Correction Factor.*—The low moisture correction factor (.08) tends to make all mineral-matter to ash ratios lower than the theoretically correct ratios and is of particular importance in the case of coals containing a large proportion of kaolinite. Since coals containing much kaolinite are usually low sulphur coals, the calculated mineral-matter to ash ratio in low sulphur and low ash coals in general tends to be lower than the actual ratio, resulting in pure coal values somewhat too low for such coals.

(2) *Pyrite versus Total Sulphur.*—One effect of regarding all the sulphur as pyritic is to assign too small a part of the ash to kaolinite. This, however, has the compensating effect of offsetting the low moisture-correction factor used for clay. A second effect is to raise the sulphur to ash ratio, thereby also increasing the mineral-matter to ash ratio. The combined effect of alloting all the sulphur to pyrite is to overcome the deficiency in the ratio due to the smallness of the correction factor for clay minerals as described under (1) above. Indeed it may be sufficient to overcome the deficiency in the ratio due to failure to make allowance for calcite, to be discussed in the next paragraph.

(3) *Disturbing Effect of Calcite.*—The effect of making no allowance for the presence of calcite is a tendency to produce a mineral-matter/ash ratio that is lower than the theoretical ratio, since the carbon dioxide required for combination with calcium oxide has ten times the weight of the moisture of hydration necessary for the same weight of clay. The county average CO_2/ash ratio for Illinois coals is .07, with variations from a minimum of .02 to a maximum of .16 for the county average values. Such ratios will increase the mineral-matter to ash ratio .06, .02, and .14 respectively, representing the approximate deficiency in the ratio when no allowance is made for calcite.

This deficiency may be important in coals containing relatively little pyrite but much kaolinite or calcite, such as the low sulphur

coals. On the other hand, it may be largely compensated for in coals in which the sulphur is high, particularly if the sulphur to ash ratio is high.

Of greatest significance are the irregularities due to the highly erratic occurrence of the calcite. Samples of coal from two contiguous parts of the same bed may vary considerably in their calcite content without much variation either in the amount of sulphur or in the total amount of ash. By the Parr formula the mineral-matter to ash ratio would be the same for the ash of both samples, whereas the theoretical ratio would be considerably higher for the high calcite coal, since the calcite is obviously displacing kaolinite. Unless a carbon dioxide determination had been run on each sample, there would be no means of determining the cause of possible discrepancies in the unit coal values. In general, it is apparent that since regarding all sulphur as pyritic tends to overcompensate the small allowance for water of hydration of the clay, the failure to make a correction for calcite is most significant in the case of low sulphur coals and those with a low sulphur to ash ratio, since ash from such coals will be derived largely from kaolinite or calcite, or both.

The general conclusions in regard to the mineral-matter values derived by the Parr formula, assuming that the minerals are calcite, pyrite, and kaolinite, and that the ash consists of the oxides represented in the minerals, are as follows:

1. The Parr formula gives mineral-matter values that are lower than the theoretically correct values if the sulphur content of the coal and the sulphur to ash ratio are low. This would result in relatively low unit coal values.

2. This error for low sulphur coals is still further increased if such coals contain calcite.

3. In coals having ash of intermediate character with respect to the sulphur content, it seems probable that the error due to assigning all of the sulphur to pyrite essentially compensates the deficiency due to the low value assigned to the water of hydration of the clay. Erratic variations in calcite, however, effect erratic variations in the mineral-matter to ash ratios of this group that are largely a matter of chance.

4. In high sulphur coals and coals in which the sulphur to ash ratio is high, there is considerable chance that mineral-matter to ash ratios will be higher than the theoretically correct values because all the sulphur is assigned to pyrite. However, this is less likely to be the case when considerable calcite is present, which is a reasonable probability.

5. The general conclusion is that there is a reasonable probability of obtaining mineral-matter values which are in close accord with the theoretically correct values by using the Parr formula, except possibly in the case of low sulphur coals and particularly those having a low sulphur to ash ratio.

EVALUATION OF THE THIESSEN FORMULA.

The Thiessen formula is identical with the Parr formula except that it corrects for the presence of calcite. It is obvious that this will in every instance in which calcite is present increase the mineral-matter to ash ratio. It has been shown that need for such increase apparently does not exist for Illinois coals except in the case of the low sulphur coal, particularly those having a low sulphur to ash ratio. Information is not available at present to indicate the exact limits within which this correction should be applied.

It has been observed that calcite probably effects considerable irregularities in the mineral-matter values in the high sulphur coals, but it has also been shown that departures from the theoretically correct values are due largely to the deficiency of calcite rather than to its presence. If deficiencies in calcite occur, the sulphur correction over-compensates the error arising from the small hydration factor for clay. If calcite were present this over-compensation would be less probable. Since calcite is usually present, the general application of the calcite correction would probably result in an average excess of mineral matter values.

APPLICATION TO DETERMINED VALUES.

In order to demonstrate some of the characteristics of the values derived by the Parr and the Thiessen formulæ, the results

obtained by the application of the formulæ to the theoretical ash are compared with the amounts of the determined mineral matter as found in the New Orient coal. In Table IV are given the following data:

(1) The total mineral matter in each bench (from Table I);
(2) the theoretical ash value derived from the minerals shown in Table I;
(3) the amount of derived pyritic sulphur (Table I);
(4) the additional amount of organic sulphur in the coal as determined by chemical analysis;
(5) the total sulphur (col. 3 + col. 4);
(6) the derived mineral carbon dioxide (CO_2) from Table I;
(7) determined mineral-matter to theoretical ash ratios, these being regarded as theoretically accurate.

TABLE IV.

MINERAL-MATTER TO THEORETICAL ASH RATIO COMPARED WITH RATIOS OBTAINED BY FORMULA.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Block No.	MM %	Ash %	S_P %	S_o %	S_T %	CO_2 %	MM:Ash Col. 1 : Col 2	Parr				Thiessen			
								With S_P (a)		With S_T (b)		With S_P (c)		With S_T (d)	
								MM %	Col. 8 : Col 2	MM %	Col. 10 : Col 2	MM %	Col. 12 : Col 2	MM %	Col. 14 : Col 2
V	3.15	2.16	0.97	0.70	1.67	0.28	1.46	2.86	1.33	3.23	1.50	3.12	1.45	3.50	1.62
IV	1.49	1.24	0.05	0.58	0.63	0.03	1.20	1.37	1.10	1.70	1.36	1.39	1.12	1.71	1.38
III	2.51	2.04	0.17	0.42	0.59	0.07	1.23	2.30	1.14	2.52	1.24	2.36	1.17	2.59	1.27
II	7.30	4.99	0.05	0.34	0.39	1.86	1.46	5.42	1.086	5.60	1.12	7.09	1.426	7.28	1.46
I	4.27	2.84	0.01	0.35	0.36	1.21	1.50	3.07	1.082	3.26	1.15	4.16	1.472	4.35	1.54
II-IV	2.79	2.15	0.11	0.45	0.56	0.30	1.30	2.38	1.11	2.63	1.22	2.65	1.24	2.90	1.35
I-V	2.98	2.22	0.24	0.48	0.72	0.38	1.34	2.53	1.14	2.79	1.26	2.87	1.29	3.13	1.41

(*a*) MM/Ash = 1.08 + .55 S_P/Ash
(*b*) MM/Ash = 1.08 + .55 S_T/Ash
(*c*) MM/Ash = 1.08 + .55 S_P/Ash + .9 CO_2/Ash
(*d*) MM/Ash = 1.08 + .55 S_T/Ash + .9 CO_2/Ash

Using the above data and the Parr and Thiessen formulæ, the following values are obtained:

(8) and (9) calculated ash and mineral-matter to ash ratios, using the Parr formula and the values for pyritic sulphur;

(10) and (11) calculated ash and mineral-matter to ash ratios, using the Parr formula and the values for total sulphur;

(12) and (13) calculated ash and mineral-matter to ash ratios, using the Thiessen formula and the value for pyritic sulphur;

(14) and (15) calculated ash and mineral-matter to ash ratios, using the Thiessen formula and the values for total sulphur.

Consideration of the values given in Table IV in general substantiates the generalizations previously stated in regard to the usefulness of the Parr formula. The variations in mineral content represented are considerable: kaolinite, 35 to 90%; pyrite, 0.5 to 57%; calcite, 4.5 to 65%. This is about as wide a variation in the proportion of the minerals as one would expect to find in even a wide variety of coals. The values may be considered bench by bench:

Bench V. This mineral matter consists of a high proportion of pyrite and equal portions of kaolinite and calcite. The best agreement is obtained by the Thiessen formula, using pyritic sulphur. The Parr value is high, indicating an over-correction due to regarding all sulphur as pyritic.

Bench IV. The mineral matter is largely kaolinite with little pyrite and calcite but with a high S/A ratio because of the low ash. The Thiessen formula using pyritic sulphur gives the best agreement, indicating that the sulphur correction for the Parr formula considerably over-compensates for the error in the hydration factor and that additional correction for calcite is undesirable.

Bench III. This is a high kaolinite, medium pyrite and low calcite ash. The best agreement is with the Parr formula, indicating that a relatively small amount of total sulphur will tend to correct errors in the hydration factor. Since pyrite is commonly present in a greater amount than this in Illinois coals, the Parr formula probably gives results that are mostly too large for such coals.

Bench II. This is a high calcite, medium kaolinite and low pyrite coal. The Parr value is very low. This is the type of mineral matter to which the Parr formula is least adapted and the Thiessen formula best adapted, since a correction for calcite is essential for agreement with the theoretically correct values.

Bench I. This mineral matter is essentially similar to that found in Bench II, and the results substantiate those obtained for Bench II.

Benches II to IV. The average character of these benches provides mineral matter relatively high in kaolinite and calcite and low in pyrite. As is to be expected, the Parr values are low, but the application of the calcite correction (column 15), although it gives the best agreement, is rather high, indicating that with a slightly higher sulphur value the calcite correction would probably be superfluous.

Benches I to V. This represents the entire seam, with mineral matter content that is more or less intermediate. The Parr value is too low but the Thiessen formula gives a value almost equally too high. It is apparent that whether or not the calcite correction is advisably applied to these coals is largely a matter of chance if no information in regard to the character of the ash is available aside from that supplied by the CO_2 determination.

These studies indicate that for an ash derived from the three minerals predominating in New Orient coal, the Parr formula using total sulphur values gives mineral-matter to ash ratios which are in satisfactory agreement with theoretical values for coals having an ash of an intermediate character (Bench III). When the kaolinite and calcite values are high, particularly the latter, and the sulphur to ash ratio is relatively low, the Parr formula gives values that are distinctly lower than the theoretical values and a correction for calcite is desirable (Benches I and II). Coals that are relatively high in pyrite yield an ash which, corrected by the Parr formula, gives values that are relatively high (Bench V). This is particularly the case if the sulphur to ash ratio is high (Bench IV). Such a relationship is likely to exist in coals with low pyritic but high total sulphur. It is important

to realize that with respect to sulphur it is the sulphur to ash ratio that is important and not the sulphur content. Ordinarily, however, the coals high in pyrite have a fairly high sulphur to ash ratio. Low sulphur coals will have a high sulphur to ash ratio only when the ash is unusually low.

CONCLUSION.

The systematic separation of the mineral constituents by physical means from a column of representative Illinois coal justifies certain conclusions in regard to the prevailing constitution of the mineral components. The predominating minerals in the coal are calcite, pyrite, and kaolinite. Chemical analysis of the ash indicates the presence in some instances of considerable amounts of silica, the nature of which is unknown. Other mineral substances are present in unimportant quantity.

On the assumption that the quantity of the predominating minerals, calcite, kaolinite and pyrite, largely determines the quantity of the ash, consideration has been given to the validity of the Parr unit coal formula as a means of providing an approximately accurate mineral matter value from the items of the proximate analysis. The studies indicate that this formula, although theoretically erroneous in detail, contains compensating errors so that it will probably yield fairly satisfactory results for coals of average ash composition. Serious errors may result, however, in determining mineral-matter values for coal containing much kaolinite or calcite or both, particularly if the ratio of sulphur to ash is very low. Mineral-matter values for such coals will be too low. On the other hand, values obtained from high sulphur coals, particularly if the ratio of sulphur to ash is high, are likely to be higher than the theoretically accurate values. A general correction for calcite, such as is represented by the Thiessen formula, seems undesirable but might wisely be applied to the low sulphur coals, particularly if the sulphur to ash ratio is also low.

The effect of a quantity of free silica in the mineral matter has not been considered, but since it would not change in ashing,

the general effect would be to compensate for errors in the hydration factor of the clays, particularly in the high kaolin coals, thus making the correction for calcite somewhat less necessary. It is hoped that further investigation will provide more definite data in regard to the character of this constituent and the nature of its occurrence in coal.

ILLINOIS STATE GEOLOGICAL SURVEY,
URBANA, ILL.

DISCUSSION AND COMMUNICATIONS

THE PROBLEM OF THE TRANSFER OF SILICA BY WATER VAPORS.

A RECENT article in this journal by Ingerson [1] has done a service in advancing the problem of the possibility of the transfer of insoluble oxides by water vapors and other volatile compounds in solution at supercritical temperatures.

The problem of the transfer of silica by water vapors is of particular interest.

Smit [2] has theoretically constructed the equilibrium diagram of the system SiO_2-H_2O, introducing the modifications of silica. Its experimental verification has, however, hardly been started.

Willstätter [3] and his co-workers have shown the existence of a slightly polymerized silica which is partly volatile with water vapor.

Van Nieuwenburg and Blumendal [4] have made an attempt to use the transfer of silica for the synthesis of a number of silicates.

Morey [5] has repeated some experiments of the above workers and arrived at the conclusion that the reaction of silicate formation in their tests might have taken place only in the liquid phase.

Greig, Merwin and Shepherd [6] have noted the transfer of silica by gases and its deposition as crystobalite.

In 1933 the author [7] decided to verify the experiments of Dutch

[1] Ingerson, Earl: Relation of Critical and Supercritical Phenomena of Solutions to Geologic Processes. ECON. GEOL., vol. 29, pp. 454–470, 1934.

[2] Smit, A.: Rec. Trav. chim. Pays-Bas, 1930, p. 962.

[3] Willstätter, Kraut and Lubinger: Ber. Deutsch. Chem. Ges. B. 58, 2462, 1925.

[4] Van Nieuwenburg, C. J., and Blumendal, H. B.: Rec. Trav. chim. Pays-Bas, 1930, p. 857; 1931, p. 129.

[5] Morey, G.: Trans. Amer. Geophys. Union. 1932.

[6] Greig, Merwin and Shepherd. Amer. Jour. Sci., (5) 25, p. 61, 1933.

[7] Syromyatnikov, F. V.: U. S. S. R. Acad. of Sci., Trans. I. Conference on Experim. Mineral. and Petrography (with an English summary). 1934.

workers, choosing as the object of his study the synthesis of serpentine. At the same time he obtained experimental material, giving an idea of the amount of non-volatile components transferred by water vapor.

The first experiments dealt with the formation of serpentine as the result of the reaction:

$$MgO.nH_2O + SiO_2.mH_2O \rightarrow \text{serpentine.}$$

The volume of water taken was below the critical, in order that the water vapor should be superheated, thus eliminating any possibility of the water overflowing the upper crucible upon expansion.

An autoclave with an inner volume of 2 liters was used. Hence the critical volume was about 800 cc. The upper crucible with magnesium hydroxide had the upper brim at a height of 0.8 h (where h is the height of the autoclave). In the lower portion of the autoclave, water and SiO_2 were placed, preferably as freshly precipitated and washed gas.

TABLE I.

No. of Test	Volume of Water, cc.	Temperature, Deg. Cent.	Pressure, kg./cm².	SiO_2 % Weight.	Fe_2O_3 % Weight.
1	2	3	4	5	6
62	500	400	260	6.00	Undetermined
70	400	400	260	4.22	"
128	200	400	220	1.62 to 3.10	"
132	50	350	88	0.20 to 3.10	0.36

Under these conditions the transfer of silica could be brought about only by means of water vapor (gas). Column 5 of Table I shows that silica was in all cases found in the upper crucible. It is interesting to note, that the amount of silica transferred decreases with the reduction of the quantity of water used. In tests Nos. 128 and 132 are given a number of values for SiO_2. This variation is accounted for by a certain irregularity in the distribution of the serpentine formed in the mass of $Mg(OH)_2$

in the upper crucible. Generally the maximum amount of SiO_2 is found in the upper portions of this mass. In addition to SiO_2, a small quantity of Fe_2O_3 was found. For purposes of control, the reagents used were analyzed; magnesium chloride, from which magnesium hydroxide was precipitated, contained only 0.016 per cent SiO_2.

Thus, it may be stated with assurance that silica (as well as ferric oxide) is transferred by superheated water vapor and that the reaction of serpentine formation may proceed by pneumatolysis.

In addition, an attempt was made to determine the amount of silica that may be "dissolved" in water vapor (gas). For this purpose a sample of gas was taken from the above-mentioned large autoclave, which contained at the bottom 800 cc. of water and 30 g. of diatomite, at 400° C. The sample of gas was condensed, and the resulting liquid, which was turbid and of a brownish color, was carefully removed, weighed, and analyzed. The data obtained are as follows:—

Volume of liquid	260 cc.
Weight of dry residue on ignition	0.4607 g.
Amount of SiO_2 in residue	0.1944 g.
Amount of Fe_2O_3 in residue	0.2368 g.

Re-calculating into grams to a liter of water (liquid), the following solubility values are obtained:—

For SiO_2	0.74 g/liter
For Fe_2O_3	0.90 g/liter

Thus, this particular experiment also points to the possibility of the transfer of insoluble constituents.

It is thus far difficult to say whether a true (i.e. molecular) solution, or a somewhat more coarsely dispersed sol is involved. A more mechanical transfer, however, is out of the question, since precautions had been taken to avoid it.

In conclusion, another interesting aspect of the problem may be considered. If the total amount of SiO_2 that was found combined with MgO and H_2O as serpentine (*e.g.* in test No. 62) is calculated, it will exceed the amount of SiO_2 carried in 2 liters of

water vapor at 400° C. Hence, the conclusion may be drawn that diffusion of silica molecules through the gaseous medium takes place. Such an explanation is essential, since, even with no shifting of the gaseous medium, the diffusion of silica favors the formation of great quantities of silicates in rocks which can react with silica.

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MOSCOW, U. S. S. R.

ORIGIN OF THE IRON ORES OF SPANISH MOROCCO.

Sir: In his paper on the Rif iron ore deposits,[1] Professor Heim invites discussion of his genetic interpretation of the Monte Uixan ore bodies as products of magmatic intrusion. Although my own experience of this district is limited, some points of view may here be presented.

Only two modes of origin have been seriously discussed in this case. Pyrometasomatism has been the explanation most generally offered in recent years, and a magmatic nature has been advocated by Rubio (in 1912) and by others. In a discussion in this journal some years ago,[2] I accepted the pyrometasomatic interpretation as the more probable one, but also pointed out some unusual features.

Metasomatism is strongly suggested by the fact that at Uixan the ore, so far as the writer knows, occurs only in limestone, and by the presence in it of limestone inclusions (interpreted as unreplaced remnants); while magnetite[3] as the iron ore mineral, instead of siderite, indicates a temperature within the range indicated by the term *pyro*-metasomatism. The abundant pyrite is rather typical of pyrometasomatic iron ores. Unusual features, on the other hand, are the scarcity of introduced silicates (skarn), and of leaner magnetite impregnations in the limestone. As mentioned in the paper cited above, fine-grained skarn rocks may

[1] Heim, Arnold: ECON. GEOL., vol. 29, p. 294, 1934.

[2] ECON. GEOL., vol. 22, p. 559, 1927.

[3] As shown in the writer's paper just quoted, the primary ore of Uixan is mainly magnetite.

have been to some extent overlooked, but in any case the ore itself is remarkably low in silicates.

The magmatic interpretation derives its arguments chiefly from those facts just mentioned that mark Uixan as different from the more common type of pyrometasomatic deposits. The only positive argument of weight would seem to be the relations of the massive ore at Bokoya, as described by Heim. Unfortunately the details of this occurrence, including the petrographical characters of the associated rocks, are not given. For a serious consideration of the magmatic hypothesis it is necessary to inquire whether the unusual features mentioned must be regarded as definitely excluding an origin by pyrometasomatism, and also, whether the facts of the case are in any way more consistent with the magmatic interpretation.

As to the first question, it is obvious that the aberrant features are differences in degree rather than in kind, and therefore not decisive. For a comparison with magmatic ores, one must first make clear what the term "magmatic" is meant to imply in this particular case. There are two known types of magmatic iron ores. One is represented by the titaniferous ores, always in intrusive rocks of a more or less gabbroid character. The other type is the one often named from Kiruna, practically non-titaniferous, and associated mainly with syenitic or dioritic rocks of an effusive or hypabyssal origin. Although details in the process leading to the forming of such ores are still obscure, the main features seem to the writer to be about as clear as in any other type of ore deposits, residual magmas being indicated, grading into pneumotectic bodies and further in places combined with metasomatic action of a pyrometasomatic or even hydrothermal character.[4]

Of these two types, the first is obviously excluded in this case, and it remains only to compare Uixan with the Kiruna type. The character of the ore itself and its gangue is about as consistent with this interpretation as with the pyrometasomatic alternative, although the content of pyrite is much higher than in

[4] For further data, compare the writer's paper: Iron Ores of the Kiruna Type. Geol. Survey of Sweden, ser. C, no. 367, and papers quoted there.

any ore body referable to the Kiruna type, and, on the other hand, the absence of noticeable apatite is striking. Also the associated igneous rock, a porphyritic diorite, is of a general character known to be combined in some places with ores of this type. But a feature that distinguishes Uixan from the Kiruna type is the fact that the ore appears to be almost restricted to the limestone, and not typically connected with the igneous rock. In the Kiruna type, the ore bodies giving evidence of a magmatic or pneumotectic origin are always found in the igneous mother rock. Deposits in limestone are associated in some cases (Ural Mountains, Russia, Iron Springs district, Utah), but always prove to have arisen through the metasomatic action of solutions related to the magmatic products.

Thus, Uixan differs about as much from the clearer examples of magmatic iron ores as from the pyrometasomatic group, perhaps even more. From what the writer has seen of the Huelva pyrite deposits, and from considerable experience of certain other pyrite deposits that have closely similar geological characters, reference to this type hardly strengthens the case for a magmatic interpretation.

It is not the meaning of these lines to champion the pyrometasomatic interpretation of Uixan, but to point out that a satisfactory solution of the problem cannot be reached without more detailed geological and petrographical studies.

PER GEIJER.

DJURSHOLM, SWEDEN.

REVIEWS

The Iron-ore Deposits of Bihar and Orissa. By H. CECIL JONES. Geol. Surv. of India, Mem. LXIII (*2*), 1934. Pp. 167–302; pl. 13–32, two maps. Price, 13 s. or Rs. 7/10/0.

Geologists in India have long awaited an account by Mr. Jones of the iron-ore deposits in Bihar and Orissa, which he has been intermittently mapping during a period of 13 years. This readable and beautifully illustrated memoir must be regarded as authoritative. To date, detailed descriptions of these most important iron-ore resources in India have been few.[1]

The memoir is divided into two parts: Part I deals with the geology of the region, Part II describes individual iron-ore deposits. The map, covering an area of over 3,000 square miles, is the composite production of some six Geological Survey officers who worked in this region at different periods between 1919 and 1930.

The diverse rocks in such a wide area usually provide many stratigraphic and structural problems, and, as the reviewer knows only too well from personal acquaintance, this area is no exception. But the reader who anticipates enjoying the detailed discussion of such problems in this memoir remains unsatisfied. Considering the vast amount of material available, it is the one fault of this fine work.

The stratigraphical succession is arranged as follows:

Newer dolerite dikes and sills.	
Ultrabasic igneous intrusive rocks.	Archean.
Granitic rocks.	
Iron-ore series (Newer Dharwar).	
Older Dharwar.	

Other geologists have shown that the ultrabasic igneous rocks in Singhbhum are pre-granite; Mr. Jones advances no reliable evidence for moving them to a position higher in the time scale.

The Iron-ore series is all-important, as it includes the great iron-ore

[1] The paper by Dr. Percival,— "The Iron Ores of Noamundi" (Trans. Min. and Geol. Inst. of India, *26* (3), 1931) has been the only account of geological importance.

deposits of Bihar and Orissa. This series is divided stratigraphically as follows:

Upper shales with epidiorite and ash beds.
Banded hematite-quartzites with iron-ore bodies.
Lower shales with occasional thin sandstones and calcareous bands.
Limestones (in places).
Purple sandstones with a basal conglomerate in parts.

The author does not mention that the lower shales, several thousand feet in thickness elsewhere, are entirely absent in Keonjhar State; here the banded hematite-quartzites rest directly on the (presumably) basal sandstones. This feature may have an important stratigraphical or structural bearing on any discussion of the origin of the iron ores in Orissa.

The significance of the conglomerates, which are met with in the higher horizons of the series, does not appear in the development of any theme of iron-ore genesis. Other such problems are ignored.

Part II is a feast of detail, descriptive and useful. The reader's interest is coaxed with an entertaining history of the development of iron-smelting in India; there follows a complete description of the mineralogical and petrological nature of the various types of ore. Structural features and distribution of the ore-bodies are briefly outlined. A section on the enrichment of various ore types is written with fine clarity, and the author's views here will be supported by most field geologists. The discussion of the origin of the iron-ore formations as a whole, however, merely reiterates old ideas, more especially those of Leith. This attitude is, perhaps, admirable to those geologists who have accepted these ideas *in toto*, but it provides no advancement in thought. Mr. Jones appears to accept implicitly the view that the deposits and associated rocks originated in the form of marine chemical sediments. Surely he must have something additional to contribute to this discussion from the vast amount of evidence available in the Indian deposits. The reviewer has attempted to fill the gap, from his own experience of these rocks, in a paper submitted to this journal [to appear in a later issue].

Detailed estimates of each deposit are given; the total reserves of ore containing not less than 60 per cent. Fe in Bihar and Orissa are over 4,000 million tons.

The memoir concludes with excellent descriptions of each individual deposit; this section is Mr. Jones' finest monument to his work in India.

G. A. Dunn.

Geological Survey of India,
Calcutta.

Prospecting for Gold and Silver, by E. M. SAVAGE. Pp. x + 307, figs. 98. Flexible, 4½ x 7. McGraw-Hill Book Co., N. Y. and London. Price, $2.50.

This excellent little book gives, in simple and clear language, all the information needed by the inexperienced person who enters the game of prospecting for gold and silver, beginning with a brief description of some of the more important geological principles, which it is expedient for the prospector to understand.

It then discusses placers. Directions are given for staking and developing claims, for making the appliances necessary for their working, and for testing the value of the products obtained. Instructions for the operation of all the appliances used and descriptions of the processes employed in cleaning the products are all outlined, in what the author calls "operation sheets," in a way that cannot be misunderstood.

The discussion of hard-rock prospecting is introduced by a short account of the minerals likely to be encountered, including satisfactory methods for their identification and for testing their approximate values as ores. This is followed by short chapters dealing with the essential features of mining laws, with precise directions for staking out claims and securing patents on them. Instructions are also given in the methods of simple surveying, both above and underground, the making of a contour map, the determination of the intersections of adits and veins, etc., in sufficient detail to serve all practical purposes. Advice in the use and handling of explosives occupies a short chapter and then about 50 pages are devoted to the sampling and evaluation of an ore. This subject is exceptionally well handled. The instructions for sampling are explicit and are illustrated by examples worked out in detail; the directions for estimating the quantity of ore available and its value are clear and precise.

About everything that the beginning prospector needs to know is to be found somewhere in the book. It closes with chapters giving advice on buying and selling prospects, on first aid, and on taking care of one's self in wild and arid country. It is a little book that anyone with ordinary intelligence can understand. It is to be recommended for the simplicity of its statements, the directness of its instructions and the clearness of its significant figures.

W. S. BAYLEY.

The Dinosaurs: a Short History of a Great Group of Extinct Reptiles. By W. E. SWINTON. Pp. 233, figs. 20, pls. 25. Thos. Murby & Co., London, 1934. Price, 15 s.

In his preface the author explains the publication of his book as due to the fact that "this great piece of the Earth's history has never had a

comprehensive book of its own"; and that "I believe the Dinosaurs are . . . a notch on the alpenstock of time." After a general introduction, the book continues with an untechnical description of the features of Dinosaurs; an outline of the characteristics of the "Age of Reptiles" and of the distribution of Mesozoic rocks; a discussion of the origin of the beasts; an account of their anatomy and a brief statement of their classification as now generally accepted, with a few minor modifications. In the text the forms are divided into the Saurischia and the Ornithischia. The former are separated into the sub-orders Theropoda and Sauropoda, and the latter into the sub-order Ornithopoda or bipedal forms, and an unnamed suborder including the quadrupedal, armored forms—the Ceratopsia and Stegosauria of Williston.

The main portion of the volume is devoted to descriptions of the various species and an account of their habits, as inferred from their structure. One interesting chapter deals with the causes of the extinction of the group. Excellent photographs of dinosaur skeletons and of reconstructions of their external forms by the author and Mr. Vernon Edwards illustrate the text. The book is easy to read and should be of interest to non-professional students of geology and zoology and to that portion of the reading public that is curious about the great extinct reptiles of Mesozoic time.

W. S. BAYLEY.

Ores and Industry in South America. By H. FOSTER BAIN AND T. T. READ. Pp. 381. Harper & Brothers, New York, 1934. Price, $3.50.

This publication of the Council on Foreign Relations results from a series of discussions held by the Minerals Study group in 1931 and 1932 to consider the mineral resources of the South American countries.

The book is a pleasing blending of geology, geography, and economics. For each separate country there is a discussion of the main geological and geographic features; a history of the development of the mineral resources; the status of the present and future possibilities of the chief mineral resources and discussions of the important mines or mining companies. Two chapters, one on "Who owns the Mines of South America?" and another on "What of the Future?", conclude the book. Of particular interest are the discussions of the Chilean government policies.

The book is well written, interesting and informative.

Copies of books mentioned under "Reviews" or under our "New Book List" (see advertisement page) may be purchased through our Journal Bookshop by writing to W. S. Bayley, University of Illinois, Urbana, Ill.

BOOKS RECEIVED.

DAVID GALLAGHER.

Problems of Petroleum Geology—A Symposium. Ed. by W. E. WRATHER AND F. H. LAHEE. Pp. 1073. Amer. Assoc. Petrol. Geologists, Tulsa, Okla., 1934. $6.00. This Sydney Powers Memorial volume is a compilation of 43 new papers by 47 authors, dealing with the origin, evolution, migration, accumulation, and relation to structure, of petroleum, and its relation to reservoir rocks, oil-field waters, and temperature gradients. (To be reviewed later.)

Minerals Yearbook, 1934. O. E. KIESSLING AND OTHERS. Pp. 1154. U. S. Bur. of Mines, Washington, D. C., 1934. $1.75. The second volume of the new series, which is a prompt and expanded revision of the former Mineral Resources. Authoritative detailed data on domestic and foreign mineral production by various writers.

Geophysical Prospecting, 1934. Amer. Inst. M. and M. Eng., vol. 110. New York, 1934. $5.00. Papers and discussions presented at the 1932, 1933 and 1934 February meetings of the Institute.

Historical Geology. W. A. VER WIEBE. Pp. 162, figs. 206. Photolithoprint reproduction by Edwards Brother, Inc., Ann Arbor, Mich., 1934. A text for elementary students, in which the author proposes to treat the subject by reversing the more commonly used chronological order, on the basis of the well known principle of proceeding from the known to the unknown. He therefore works back through the Quaternary, Tertiary, Mesozoic, and Paleozoic; but it is interesting to note that within each one of these groups he finds it expedient to follow the usual chronological order.

China's Geographic Foundations: A Survey of its Land and its People. G. B. CRESSEY. 1st ed., 2d Imp. Pp. 436, figs. 197. McGraw-Hill Book Co., New York, 1934. A well written, well illustrated, up-to-date treatment of the topography, climate, people, national resources and products, trade, and politics, giving a rounded picture of the country and its people, and an understanding of their problems.

Weather Proverbs and Paradoxes. W. J. HUMPHREYS. 2d ed., pp. 126. Williams & Wilkins, Baltimore, 1934. $2.00. An interesting book of weather lore for the lay reader, in which various weather proverbs are discussed and the few correct ones separated from the many erroneous ones.

A Manual of Thesis-Writing for Graduates and Undergraduates. A H. COLE AND E. W. BIGELOW. Pp. 48. John Wiley & Sons, New York, 1934. 75 cts. Useful suggestions covering composition, arrangement of material, form, proof corrections, etc.

Geology of the Country around Filabusi, Insiza District, Southern Rhodesia. J. C. FERGUSON. Pp. 179, pls. 21, map in color. Southern Rhodesia Geol. Surv. Bull. 27. Salisbury, 1934. 5/4. Geology and production; 130 gold deposits, other mineral products also; interesting and complex geology; fine illustrations.

Slocan Mining Camp, British Columbia. C. E. CAIRNES. Pp. 137, pls. 13, figs. 9, maps in color. Canada Geol. Surv. Mem. 173. Ottawa, 1934. 50 cts. Silver, lead-zinc, and some gold; full treatment of general and economic geology.

Surface Deposits and Ground-water Supply of Winnipeg Map-area, Manitoba. W. A. JOHNSTON. Pp. 110, figs. 3, tables 12, 2 maps in color. Ottawa, 1934. 25 cts.

Report of the Committee on the Measurement of Geologic Time. A. C. LANE, Chairman. Pp. 86. National Research Council, Washington, 1934. Account of world research and progress, together with brief statement of much of the known data.

Gold Coast Colony Geol. Surv., Annual Report, 1933–34. N. R. JUNNER. Pp. 21. Accra, 1934. 2/. Administrative report, geologic notes.

Geology and Ore Deposits of the Breckenridge Mining District, Colorado. T. S. LOVERING. Pp. 64, pls. 15, figs. 28, maps in color. U. S. Geol. Surv. Prof. Paper 176. Washington, 1934. $1. Full geological description, much interesting detail.

Chumbo e Prata no Brasil. O. H. LEONARDOS. Pp. 116, pls. 24. Serv. de Fomento da Prod. Miner. do Brasil, Bol. 2. Rio de Janeiro, 1934.

Geology of the Country Between Springs and Bethal (South Africa). F. A. VENTER. Pp. 85, pls. 3, figs. 3. Explanation of Sheet No. 51 (Bethal). South Africa Geol. Surv., Pretoria, 1934. 5/ incl. map.

Rock Wool from Illinois Mineral Resources. J. E. LAMAR, H. B. WILLMAN, C. F. FRYLING, AND W. H. VOSKUIL. Pp. 262, figs. 34, tables 39. Illinois Geol. Surv. Bull. 61. Urbana, 1934. Extensive and detailed investigation of the geology, chemistry, and economics of rock wool.

Geology and Mineral Deposits of Salmo Map-area, British Columbia. J. F. WALKER. Pp. 102, pls. 3, map in color. Canada Geol. Surv. Mem. 172. Ottawa, 1934. 25 cts.

The Lower Gondwana Coalfields of India. C. S. FOX. Pp. 386, pls. 14, map in color. India Geol. Surv. Mem. vol. LIX. Calcutta, 1934. Rs. 8–4 or 14s.

Uganda Geol. Surv., Annual Report and Bulletin for 1933. E. J. WAYLAND ET AL. Pp. 93, sketch map. Entebbe, 1934. 4/. Administrative report, together with many brief statements on the geology and mineral resources.

Arizona Lode Gold Mines and Gold Mining. E. D. WILSON, J. B. CUNNINGHAM, AND G. M. BUTLER. Pp. 261, pls. 6, figs. 27. Arizona Bureau of Mines, Bull. 137. Tucson, 1934. Geology, history, production, etc., of the mines; hints on mining law, mine operation, and prospecting.

SOCIETY OF ECONOMIC GEOLOGISTS

The Annual Meeting of the Society of Economic Geologists for 1934 will be held in New York from February 18 to 21, 1935. Sessions will be conducted jointly with the Section of Mining Geology of the American Institute of Mining and Metallurgical Engineers in the building of the United Engineering Societies (29 West Thirty-ninth Street, New York, N. Y.). The program of the meeting will be announced in the near future.

At a meeting of the Council of the Society at Rochester, New York, on December 27, 1934, the following new officers were declared elected:

President for 1936—Donnel F. Hewett.

First Vice-President for 1936—John Wellington Finch.

Councillors for 1935–36—George M. Fowler, Donald C. Barton, Ernest F. Burchard.

Regional Vice-Presidents for 1935:

Leopold Reinecke	For Africa
Takeo Kato	For Asia
L. K. Ward	For Australia
Robert Heron Rastall	For Europe
J. B. Tyrrell	For North America
Warren F. Walker	For South America

The following new members were elected:

Manuel Santillan, Mexico, D. F., Mexico
Clarence Walter Vaupell, Mexico, D. F., Mexico.

The Penrose Medal of the Society of Economic Geologists will be awarded to Charles Kenneth Leith at the annual meeting in February, 1935.

L. C. Graton has kindly consented to serve as acting Secretary for the Society during the absence of the Secretary, from February 1 to July 1, 1935, on a trip to Australia.

SCIENTIFIC NOTES AND NEWS

Anton Gray, who left Canada last November, went to London for a short stay and from there to South Africa.

E. L. Bruce and H. C. Rickaby, of the Ontario Department of Mines, have completed a preliminary geological survey of the new Sturgeon Lake gold area east of Lake Nipigon.

H. Foster Bain left this country in December for a trip to Australia and New Zealand.

Max W. Ball, of Denver, Colorado, has recently been in Alberta examining the tar sand deposits now being developed in the McMurray area.

W. L. Whitehead, who recently returned from mine examinations in Cuba, is now in California and Utah.

Ira Joralemon gave an interesting talk before the joint meeting held in November of the Mining and Metallurgical Society and the New York Section of the Amer. Institute of Min. and Met. Engineers.

Richard Sawyer, of Butte, Montana, is now general manager of the Virginia City Gold Mining Company, Madison County, Mont.

D. C. Sharpstone, formerly chief engineer at the Roan Antelope Mine, Southern Rhodesia, has recently been doing development and examination work on properties in Alaska and British Columbia, and is opening an office in San Francisco for examination and consulting work in the West.

Harold A. Titcomb was a recent visitor in New Haven, where his son is pursuing postgraduate work in geology at Yale University.

T. J. Welcher has succeeded J. C. Ingersoll, deceased, as chief geologist for W. F. Snyder & Sons, Salt Lake City, Utah.

G. G. Dobbs and W. S. McCann are in Nova Scotia, engaged in development work on gold properties of Minerals Limited, a subsidiary of Consolidated Goldfields of South Africa.

Victor Oppenheim, geologist for the Service de Fomento da Produccao Mineral, Rio Janeiro, has completed the work of preparing a new geologic map of southern Brazil, which is now obtainable from the Director of the Service.

An International Congress of Mines, Metallurgy, and Economic Geology will be held in Paris in October, 1935. M. Cayeux is president of the Economic Geology Section, and F. Blondel is secretary. Those desiring to contribute papers should send them to F. Blondel, 13 rue de Bourgogne, Pzris VIIme.

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